Concurrent Development of a Rotationally-Symmetric Barb Joint for Modular Storage Systems through Product Innovation Research

by

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ABSTRACT

Product innovation research is the concurrent design, development and marketing of product concepts, conducted within the university environment. Driven by creative students developing their own designs, the proposed program features professorial and graduate student mentorship, engineering and non-engineering research as well as outreach to companies on new product opportunities. These projects catalyze the traditional learning process, thereby more effectively linking islands of education. The program is based upon case-studies in which students designed and developed their consumer product ideas, learning firsthand the tasks required to transform those ideas into marketable products.

The primary case-study "Modular Storage Systems" describes the development of a new fundamental joint for use in industrial and consumer product structural systems. This new class of rotationally-symmetric interlocking joint profiles includes a four-fold rotationally-symmetric barb joint that performs significantly better than the common dovetail and single barb joints. The AxiBarb™ joint is integrated into designs for Cubbeez™ modular storage systems, which are being considered by commercial enterprises for licensing and production.

Other product designs which have been monitored, supervised or co-developed include: a musical CD album; a multi-surface sponge; a lawn vacuum and sweeper; waterjet-cut stone artwork; intermeshing soap products; a flex-tuned, shoot-through archery bow riser; and retrofittable bicycle suspension systems. The product innovation projects have been conducted for over two years and have resulted in numerous pending patents and company inquiries.

Students lead the development of their innovations, which in turn helps students better focus on the fundamental knowledge and coursework needed for success. Though products are the objects of the activities, an enhanced education of broader project issues is the real product and objective of the innovation research.

Thesis Supervisor: Alexander H. Slocum
Title: d'Arbeloff Associate Professor of Mechanical Engineering

Biographical Note

Christopher M. Ho is a native of southern California and Hawaii. He received a B.S. with Honor, in Engineering & Applied Science with an emphasis in Mechanical Engineering, from the California Institute of Technology in June 1992. With a Churchill Scholarship, he received a Certificate of Post-Graduate Study in Engineering from Cambridge University, England, in June 1993. At the Massachusetts Institute of Technology, he completed the S.M.M.E. degree in February 1995. In September 1995, he began his Ph.D., specializing in Design in the Department of Mechanical Engineering. This thesis marks the completion of the doctorate degree, awarded in June 1997.

The author's graduate accomplishments include the publication of the paper "Modeling Manufacturing Quality Constraints for Product Development," with co-author MIT Prof. Kevin Otto, in the *Proceedings of the 1995 ASME Design Theory & Methodology Conference* (September 1995) as well as in *Concurrent Engineering: Research & Applications* (December 1996). He also shares U.S. and international patents pending for "Modular Storage System, Components, Accessories, and Applications to Structural Systems and Toy Construction Sets and the Like" with MIT Prof. Alexander Slocum. Christopher is a member of Tau Beta Pi, Sigma Xi, and ASME. He received a Department of Defense National Defense Science and Engineering Graduate Fellowship in 1994.

Opportunities as an undergraduate included work in Hiratsuka, Japan, on the assembly line of a manufacturing company. On a Ford Technical Scholarship, he interned at Ford Motor Co. in vehicle simulation. As a graduate student at MIT, he volunteered his services to the 2.70/2.007 Introduction to Design course for four years, assisting undergraduates design and fabricate devices for the end-of-semester design contests. He has also been an alumni area representative for Caltech Admissions and is a member of the Caltech Alumni Association and the Gnome Club.

Professional interests include product design and graphic design. He has also consulted in human factors and ergonomics, and has helped colleagues in portfolio development. Hobbies include photography and home improvement projects.

Tell me and I'll forget.

Show me and I may remember.

Involve me and I will understand.

– Lao Tzu

Acknowledgments

Thank you, Mom, Dad, Michael and Kimberley, for coping with a family member far away again. It wasn't easy, and I couldn't have done it without your love, patience, support, and sense of humor. This is the end of the degree chain for me, so let's see how it goes from here. More trials and tribulations to come, I'm sure.

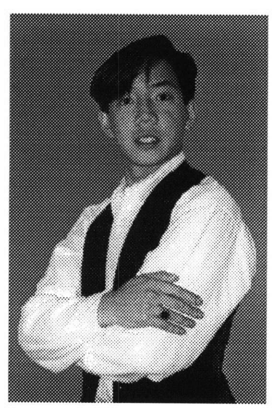
To my relatives, cousins, and family friends: we must remember that our past, our culture, and our history, form the core of the self. I acknowledge our ancestors who, by sacrifice, hard work and perseverance, overcame adversity, discrimination and misfortune, and gave us the opportunities to move forward.

May I uphold our values and maintain the family, *ohana, jia¯*.

Many thanks to Alex Slocum for believing in me. A Ph.D. in less than two years is no small matter, and your motivation and energy certainly worked wonders. You are a special friend, colleague and advisor. It was also helpful to have such a resonant sounding board, even though the board hit us on the heads every so often.

I also appreciate the guidance of my thesis committee, the camaraderie of my fellow students and peers, and the good nature of y'all in 2.70 over the years. Sharing drinks with you from the knowledge firehose of the 'Tute was a "pleasure."

Special thanks to those who walk alongside me as friends and accept me for who I am.



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Chapter 1

Introduction

Today's increasing competition among firms, to produce better products faster, places greater demands on the individuals who are responsible for the design, development and marketing of new products. This pressure on the employee translates to similar pressure on students of universities to have enhanced skills and experience upon graduation.

However, the traditional model of the university and the typical activities of a business leave a gap of experience which graduates must bridge in order to be adequately prepared for a career in business and engineering. This is especially true if they pursue leadership positions and management roles in a larger firm, or if they wish to become entrepreneurs in smaller start-up efforts. The collective experiences and skills, both managerial and technical, theoretical and applied, necessary to attain advanced positions early-on can be difficult to attain in school.

The National Research Council's Board on Engineering Education states:

> Content-based learning alone must not drive engineering education. The primary aim will be to instill a strong knowledge of *how* to learn while still producing competent engineers who are well-grounded in engineering science and mathematics and have an understanding of design in the social context.[1]

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[1] *Reshaping the Graduate Education of Scientists and Engineers,* Committee on Science, Engineering, and Public Policy (National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine). National Academy Press, Washington, D.C., 1995; pg. 3.

There is still progress to be made in engineering education, including this "social context" (non-engineering issues) of design. This thesis addresses the often conflicting natures of industry requirements and expectations with the university role of producing graduates qualified to become effective leaders of industries, especially in new-product enterprises. An integrated program of pursuing idea generation, innovation, product development and marketing while in school is proposed. This program, illustrated by a case study of an invention carried through to potential commercialization, is designed to have potentially great benefits to both the university system and participating companies, as well as to the participating students.

Given the requirements of industry and the existing operating mode of universities, it is hypothesized that there exist solutions that maintain the current organization and structure of companies and schools while progressing the education and preparation of its students by considering the following actions:

- *Extended timeline:* longer-term support for student-driven innovation activities unencumbered by current semester schedule limitations.
- *Shift in advisory roles:* more mentoring and motivating by university advisors and industry sponsors to improve student learning, experience and transportable skill development.
- *Freedom from traditional molds:* recognize various levels of autonomy and involvement in development projects, and acknowledge new methods of education and working modes.
- *Empowerment of innovators:* shift, as much as possible, project definition, decision-making, resource allocation, responsibility, and evaluation to the students.

Integration of these modifications into a cohesive product innovation program reflects the primary thesis contributions, summarized as:

- A method for cohesively integrating activities such as product development, market research, and business into the educational program, possibly as a new engineering -business degree path.
- A method for actively linking product development with industry.
- As a demonstration of the above, a fundamental new product concept presented as a case-study within this thesis.

This method of developing the student through developing innovations is illustrated by a real product project, the results of which further not only the field of engineering but also the methodologies used to conduct applicable research and development. At stake is revitalizing the basic foundations of university and industry strengths while increasing the productivity, education and value of innovative students and their qualifications.

This first chapter alludes to the current state of industry, universities and students by considering education, product development and professional preparation. Specifically, Section 1 raises four related questions that address the need for improvement in the structure of the current university-business relationship. Section 2 defines further the purpose and goals of this thesis and its intended benefits and contributions. Section 3 outlines the organization of the thesis.

1.1 Research Motivation: Gaps Between Education and Business

Prospective employees and company recruiters alike understand the conflict well — companies expect or require that an incoming employee have experience, but the person may not have had the opportunity to work on a "real" project unless hired so that the experience can be gained. This example of the chicken-and-the-egg conflict certainly exists for university graduates seeking their first full-time career position. While university activities and courses, and even internships and co-ops, can provide exemplary background for a graduate, it may fail to satisfy the desired skills and experience for the workplace. A logical goal is thus to find another way to provide "real" experience to a prospective employee *before* he or she applies for the job. Hence, the first question arises,

> Q1: "How can the prospective employee, the recent graduate, gain more applicable experience and adequate preparation for a desired job through education?"
>
> Lemma Q1: "How can the in-situ experience-gaining help the students/employees better select the major which truly interests them and in which they will work for long-term careers?"

The question Q1 to the source of valuable experience may be exacerbated by the current role of the university, its responsibility to the students and the basic contrast of that role to industry practices. While it is assumed the university, in engineering school, for example, teaches up-to-date and applicable skills to future workers in industry, students are still taught theory and research methods which may be less immediately applicable to the working world. There exists a gap between the university and industry trains of thought.[2,3] This thesis poses a second question:

> Q2: "How can the university better address the immediate post-graduation needs of graduates within the current organizational structure *and* enhance its role as a source of ground-breaking research, long-term fundamental education and theory development?"

Universities across the nation have implemented changes and additions to their undergraduate and graduate curricula in an attempt to address this very question.[4] These modifications in the educational system appear in both individual courses, departmental and cross-departmental curricula and in university-industry partnerships of varying degrees. This change has been motivated in-part because of ever-decreasing federal funding for university research and of increasing competition among industries; there is a greater need for more joint projects between the university and industry institutions.[5] Thus, it can be asked,

> Q3: "How can the university and industry work together on successful projects while meeting their own individual goals and also support the students, critical elements in the process?"

For the majority of students, post-graduation plans involve either continued work in the academe as researchers or faculty or in industry as an employee. However, for a small but significant minority, entrepreneurship and business start-ups are goals[6] despite the

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[2] Noam, E. "Electronics and the Dim Future of the University" *Science Magazine*, October 1995.
[3] Valenti, M. "Teaching Tomorrow's Engineers," *Mechanical Engineering*, July 1996.
[4] Ibid.
[5] Hanson, W.C. "The Knowledge Supply Chain," MIT Leaders for Manufacturing paper, August 1996.
[6] As reported by M. Selz, *The Wall Street Journal*, reprinted in *The Orange Country Register*, Business section p.17 (Monday, Dec.30, 1996), the Entrepreneurial Research Consortium reports that "some 37 percent of U.S. households include someone who has founded, tried to start, or helped fund a small business."

scarce organizational and financial support for invention development in educational institutions. In addressing the previous three questions, a fourth question arises:

> Q4: "Can a solution to Questions 1, 2, and 3 also encourage and provide for individual invention, innovation, and entrepreneurship?"

Restating questions Q1-Q4 as guiding statements:

1. The student/employee seeks experience and adequate career preparation through education.
2. The university can better integrate post-graduate work experience into its education of fundamentals and theories.
3. The university and industry can meet their own goals as well as the students'.
4. An all-around solution encourages innovation and entrepreneurship.

These four issues regarding the relationship between the university and industry lead to the next section: student-driven new product design and hands-on idea-to-launch ("A-to-Z") activity as an educational and professional tool to benefit the student, university and industry.

1.2 Thesis Goals: Enhancing Education & Business through New Products

The basic premise of this thesis addresses development of a new educational path within the university engineering education system in order to prepare its students for "ready-to-run" entrance into the workplace. This course of action maintains the teaching of fundamental principles and exhibits a life-long learning attitude. In particular, by employing new product development as a central theme, not only will the student (and future employee) benefit, but the university and industry can also make gains through the implementation of such a program.

An assumption in this thesis is that there are no "magic formulas" that will ensure the success of a product. Instead, it is hypothesized that the best way to maximize a product's success is to execute product development and marketing processes to the fullest, simultaneously with engineering and science. In order to do so, the participants in the process must understand the product development cycle itself. As graduating students eventually become the participants in the process, some responsibility in training and preparation shifts from the workplace to the student and the university.

It is this concurrent, simultaneous execution of the business and social aspects with engineering that catalyzes the entire program of learning. It also creates the "ready-to-run" "go-getter" engineers that businesses need.

1.2.1 Fundamental Issues

Current university activities and opportunities have been reviewed in context with preparing the student for work demands in product development. These observations can be stated in the following fundamental issues:

- Student invention and innovation is often done on an ad-hoc basis.
- University-Company relationships usually originate from the company or professors initiating and driving specific projects, with significantly less up-front student input.
- Aggressively supported infrastructures do not exist for formal student invention and development.
- Design and development do not start early enough in the undergraduate curriculum and need to be built upon through correlation with coursework and laboratory activities.

As cited before, options to overcome limitations in the current environment may include:

- An extended innovation and research timeline.
- Increasing faculty mentoring and motivation of students.
- Expanding the possible routes to research projects to include entrepreneurial activities.
- Empowering the students to be more active in the total development of the engineering and business aspects of their projects.

1.2.2 Fundamental Contributions of the Thesis

In order to examine and illustrate methods to address these issues, an intense case-study on the development of an invention into marketable embodiments has been conducted and documented. The case-study reveals the intertwined tasks and details of design, development and marketing aspects of engineering and business. The study also demonstrates differences between the existing framework in education and the proposed educational tool. *This is not to say that the university goals are not being met at present; rather, this thesis work is to demonstrate how the curriculum can be enhanced by implementation of the proposed method to a more significant and formal degree.*

The short-term contributions of this thesis are methodology-, hardware- and community-related:

1. Methodology: a framework or set of guidelines to direct innovative activities, with an organized network of university and industry resources.
2. Hardware: a fundamental new type of structural joint with broad consumer product potential.
3. Community: a new template for utilizing resources such as computers and telecommunications to empower students to create products (including graphics, art, music and design) with immediate broad market potential.

By using product innovation, development and marketing in a university environment, the proposed program addresses the following long-term goals, as raised by the four questions Q1-4 in Section 1.1:

1. Better prepare the student for the workplace in terms of product development A-to-Z experience in engineering and business.
2. Revitalize education by providing new teaching and learning tools.
3. Create opportunities for industry and university cooperation.
4. Encourage invention and development and the positive "I have a dream" confidence needed to overcome obstacles to success.

A fifth goal considers the reality of maintaining such a program:

5. Establish a self-sufficient financial base from which activities 1-4 can be supported.

With continued contributions and support of the principles revealed in this thesis, it is hoped that these goals may be met in the near future.

1.3 Thesis Organization

Chapter 2 addresses the changing environment for the engineering student-graduate in the university and industry. It reviews and briefly evaluates current relationships among university, technology and business efforts. It continues by identifying non-optimal situations which can be improved. These areas for improvement or modification form the basis for the proposed system of innovation research of the thesis.

Chapter 3 presents a new philosophy of approaching university education and alternative university roles, business expectations and the student perspective. Design education and product innovation, in particular, are considered along with "outside" factors such as market forces and management tools. New product development as a common subject of attention is illustrated using a graphical representation of the relationships between people, their activities and resulting products. A classification of university-student-industry interactions is presented and compared to current and proposed project work.

Chapter 4 summarizes several consumer product projects undertaken by students that exhibit many of the concepts and principles of a proposed Product Innovation Research Program. These projects serve as examples of how and why a new activity can be formed to encourage similar product development work.

Chapter 5 documents the case-study on "Modular storage system, components, accessories, and applications to structural systems and toy construction sets and the like" invented by the thesis author and advisor. The development and progression of an invention is described, from the idea stage to the development and marketing efforts, in the university setting with industry exchange. The concepts of the advisor and student as a "thesis team" and "team partners" are illustrated. Chapter 5 also focuses on the design, engineering, manufacturing, sales and marketing aspects of the case-study. Results from engineering analyses and experiments are presented, and the application of modified management tools are discussed.

Chapter 6 relates the revelations of the case-study to the proposed model of product development in a university setting. Also, an educational program integrating engineering and business is described.

Conclusions are presented in Chapter 7.

Appendices follow the final chapter.

Chapter 2

The Changing University Environment

The traditional, albeit simplified, picture of engineering students in the university and industry settings typically follows a path of:

1. Students attend school (college, graduate school) for a number of years.
2. Occasionally, there is crossing over between the university and industry, in the form of financial support from industry for sponsored research, coursework involving some industry practice, and by co-ops or internships.
3. Some stay within the university environment as faculty, conducting research and educating the next students; the majority of other graduates enter the workplace, engineering new products and systems.

These steps are illustrated in Fig. 2.1.

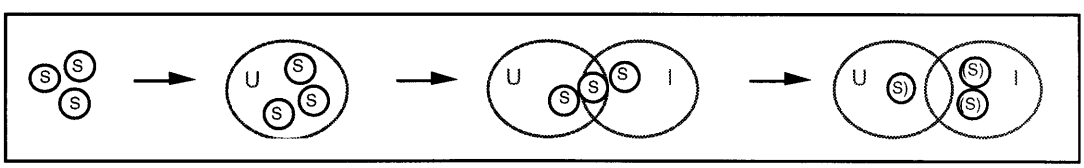

Fig. 2.1: A traditional path of engineering students. Students enter the university, learn in various courses with or without industry exposure, then enter the workforce in academia or industry.

While this model can be considered common in the United States, it may not necessarily be the optimal system for any of the parties involved (student, university, industry (and government)). The climate of the engineering community, as well as the larger market environment, is changing as the world economy and technologies change, and hence the interaction of the students, the university and industry may need to change as well. The Committee on Science, Engineering, and Public Policy comments on the situation as such:

> Hence, the three areas of primary employment for Ph.D. scientists and engineers – universities and colleges, industry, and government – are experiencing simultaneous change. The total effect is likely to be vastly more consequential for the employment of scientists and engineers than any previous period of transition has been.[7]

The National Research Council's Board on Engineering Education reports:

> The means of delivery of engineering work are also changing; engineering work is no longer delivered solely through tangible products. Engineering services ranging from designs to software systems to technology assessments are delivered electronically around the world. *Engineering education is very much an engineering service, and it, too, requires effective delivery systems.*[8] (italics mine)

The report continues,

> Given the rapidity of technological change, it is essential that the education system prepare students to function productively as engineers (whether in industry, government, or academe) over the full course of a career. *Content-based learning alone must not drive engineering education. The primary aim will be to instill a strong knowledge of* how *to learn while still producing competent engineers who are well-grounded in engineering science and mathematics and have an understanding of design in the social context.*[9] (italics mine)

Another national committee finds:

> Graduate research itself often adds significantly to the fundamental knowledge base, enabling industry to extend its own research and development. On the other hand, industry often has little influence on the direction taken by academic research, and university-trained students often have no appreciation of the constraints and drivers affecting the conduct of research by industry, or indeed of why industry should even have a stake in research. Simply put, there has been in many fields a fundamental disconnect between industry's needs and government's support for academic engineering research. ...*In view of the broad range of ways in which scientists and engineers contribute to national needs, it is time to review how they are educated to do so.*[10] (italics mine)

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[7] *Reshaping the Graduate Education of Scientists and Engineers.* pg. 3.
[8] *Engineering Education: Designing an Adaptive System,* Board on Engineering Education (National Research Council). National Academy Press, Washington, D.C. 1995. pg. 14.
[9] Ibid. pg. 15.
[10] *Forces Shaping the U.S. Academic Engineering Research Enterprise,* National Academy of Engineering. National Academy Press, Washington, D.C. 1995; pg. 8.

Hence, a need has been identified, to re-evaluate the relationship between the university and industry, suggesting that other means of achieving engineering excellence be developed and implemented. While the goal of educating engineers in fundamentals has not changed and is still appropriate for a significant portion of engineering students, additional exposure and coordination in the aforementioned social context warrants considerable attention.

This chapter gives particular attention to the student preparing in the university for a position in industry. Section 1 reviews the current activities and programs available to engineering students at MIT. Section 2 identifies areas of improvement for programs leading to product development futures, and reviews different philosophies in educational practices. Section 3 considers how to approach student motivation and incentives in learning to better instill design and engineering discipline .

2.1 Current Activities in University Programs

University education often includes coursework and hands-on projects in its undergraduate and graduate curricula. Coursework in engineering schools can emphasize both the theoretical background and the application of the theories to research or other work in progress. Similarly, in business schools, another view can be taken, from the marketing and financial side of engineering applications. Some university courses meld the engineering and management viewpoints into a single graduate course, strengthening the overall design, development and marketing process in its students.

A large portion of these projects occur in engineering design classes, in which term projects involving design and mock-up of a particular product type are guided. In MIT's Mechanical Engineering Design Division, for example, product- and industrial design take a more active role in the traditional engineering courses.

There are also other, more informal activities in some universities which also foster the entrepreneurial spirit. These can take the form of entrepreneurial clubs or inventors' associations at the collegiate level, similar in purpose as regional or national inventors organizations.

However, the university, established to attract and educate for the future, is undergoing a change in its environment. In one respect, the age-old concept of students coming to universities for its center of information and access to expects in the fields is changing due to technological advances in communication and information access.[11] How soon will it be before course lectures are self-contained in computer telecommunication resources, such as on the Internet or in local area networks, for example? Also, with cutbacks in federal funding and difficulties with financing laboratories and other facilities, there is newfound need to offer other ways to educate and inspire the students of the coming generation. While not opposing the standard form of lectures and coursework, an alternative or parallel learning experience may be offered, in the form of one-on-one mentorship in design and development, to supplement the existing framework of supporting both theory and practice. Lectures and innovation need not be mutually exclusive ; indeed, they can be supportive and complementary to one another.

Couple this with the fact that not all graduates pursue academic careers, there is the continuing requirement that a university's education should prepare the students for their forthcoming careers. Should they accept a position in an engineering or business firm, one should expect that they have adequate training and exposure to the techniques and skills that will be required of them without undue relearning or retraining.

2.1.1 Coursework at MIT

MIT is currently a recognized leader in educating engineers, at both the undergraduate and graduate levels. In recent years, there has been a revitalization of the mechanical engineering course curriculum to more fully enable its students to take part in hands-on learning and in product design and development. Similarly, MIT's Sloan School of Management contributes to product innovation in joint courses with engineering as well as management courses primarily devoted to innovation in the company setting.

Mechanical Engineering: Undergraduate Courses

The Design/Manufacturing Stream is a set of three undergraduate courses focusing on design and manufacturing in engineering. The project-based courses are required for the Bachelor's Degree in Mechanical Engineering and recommended to be taken in sequence

[11] Noam, E. 1995

over three years. The first of these courses is 2.007 Design and Manufacturing I. In this course for sophomores, the design process is introduced, and a term-long project is provided: design and fabricate from a standard assortment of materials and components a "one-of-a-kind" device that will perform better than your opponent in a predefined table setup. The course culminates in a single elimination contest in which all students partake.

2.008 Design and Manufacturing II continues this design and manufacturing stream by exposing students to manufacturing processes, machines and performance criteria. Manufacture of a low-volume product (such as a yoyo) demonstrates by hands-on interaction the concepts and principles.

2.009 Product Engineering Processes is the third installment of the design and manufacture course stream. In this course, the product development model is carried further to involve design and development of a larger, more complex product, resulting in the term-long high-quality functioning prototype. Market research and customer information are key elements of the project content, and teamwork, communication and presentation skills are essential for successful completion of this course.

These courses intend to teach and demonstrate the fundamentals of design and development through increasingly complex projects. While industry practices are introduced and exposed to the students and teams, the work is done almost entirely within the university environment. Also, the projects seldom progress beyond the end of term.

In another course, 2.72 Elements of Mechanical Design, outside sponsors provide design problems and fund the design of products for these situations. Student teams work to produce design plans and drawings which could be used to fabricate the product. A second semester follow-up course, 2.721 Design for Production, is offered to allow for the actual fabrication and construction of the design.

Additional undergraduate courses, such as 2.737 Mechatronics, are also project-based electives, providing the students with hands-on "active" learning. All of these courses have shown that theory and principles learned in the lecture hall are applicable and necessary in the design rooms and the manufacturing settings. Also, the personal supervision and instruction during the design and fabrication is deemed as vital towards the understanding by the students of the tasks at hand. For example, the seemingly simple concept of bolt selection, while mentioned in lecture, would be difficult to explain without demonstration and use of actual bolts, and at least an explanation of the alternatives to bolts. To have students carry out the decision-making process, and their experience in successes and failures, is the next necessary step taken by these design courses.

Mechanical Engineering: Graduate Courses

Graduate courses, like the undergraduate courses in the department, often consist of term-long projects to demonstrate principles and allow the students to implement the lessons on products.

2.74 Optimal Product Redesign features the redesign of a consumer product. Customer interviews, benchmarking studies and optimization analysis is used to improve the design of the product, and the results of those studies are used to fabricate a prototype of the improved product.

2.744 Product Design considers the voice of the customer, human factors, ergonomics, and similar product design essentials. Individual and team projects allow students to combine their creativity and design abilities with customer and market studies, resulting in mock-ups simulating the proposed end product.

Manufacturing is central to 2.810, a course where student teams design, manufacture and operate an radio-controlled toy car. Students operate or participate in several manufacturing processes to make components for their project, allowing for the design and manufacturing principles to be applied firsthand.

2.891 Management for Engineers takes a different path in engineering education. This course uses case-studies as the basis for its discussions. Students consider the non-technical aspects of business in technological fields and products, and are concerns with management issues and techniques.

Collaborative efforts between the School of Engineering and the Sloan School of Management also exist to help bridge the gap between engineering and business perspectives. Cross-listed course 2.739/15.783 focuses its attention on the initial development of an original product idea and a prototype while providing information on the marketing aspect of the product. In some cases, there is an industry sponsor as well as resources as design schools for industrial design.

Related Courses in Other Departments

In both engineering departments and in non-engineering schools at MIT, there are courses that are applicable and relevant to design, development and marketing of products. For example, other departments in the School of Engineering have numerous design project courses in which students can design and fabricate products and system devices. Other courses provide insights in the management or business aspects. Two such courses are:

6.931 Development of Inventions and Creative Ideas is a course that reviews the challenges and issues behind invention and patent law. Cases are discussed to shed insights for students interested in inventing, innovating and following up on those ideas to commercialization.

15.351 Management of Technological Innovation is devoted to the discussion and application of management analysis tools to the competitive technologically-advancing market. Case-studies are central towards the discovery of the issues, and class discussion and evaluation assist in relating insights to one another.

2.1.2 Research Programs

Undergraduate Research Opportunities Program (UROP)

Research also provides undergraduates and graduates with the opportunities to engage in independent work which may lead to invention and development. The Undergraduate Research Opportunities Program (UROP) enables undergraduates to partake in research, often of their own choosing, that allows them to experience research and tasks that would otherwise be research for graduate students and faculty at other universities. In some cases, these opportunities involve invention and patenting of product concepts. These results may then available to other researching students development and marketing, though this continuation must often transpire separately from any course timeline or examination schedule. Nonetheless, UROP demonstrates a range of projects and motivational levels which make this kind of program a valuable resource.

Graduate Research

Highly dependent upon the type of research and the level of theory or practice, graduate research in Mechanical Engineering may not involve the whole design, development and marketing process. In some cases, the work is purely within the laboratory or academic environment, requiring little contact with outside firms and thus minimally influenced by industry practices. As the emphasis is on fundamental discovery, original work and proof of concept, full-blown implementation is usually not a high priority objective.

On the other extreme are those graduate students who engage in design and development of products and processes more closely aligned with industry conventions and standards. In these cases, the interaction between the industry and the students involved may serve as an education for the student in industry practice. While the output of the research may be feasible and worthy of market exposure, the emphasis is on fundamentals and technical work and less priority on marketing and business issues. Since the project is sponsored within a research group or field, the choice of project may also be limited to the area of interest of sponsors or the advising faculty member.

New Products Program

The New Products Program was a recent attempt in the Department of Mechanical Engineering at MIT to join the resources between sponsor companies and master's candidate graduate students. Students admitted and accepted into the program would be placed on a product design and development project in participating companies. Firms would introduce a more independent contributing student into their design process, and in return, the student would learn about the company's practices and methods. For various reasons, however, this program recently ceased operations.

Leaders for Manufacturing (LFM) Program

The LFM Program is a partnership between MIT and over a dozen manufacturing firms in the United States. A dual degree program between the Sloan School of Management and the School of Engineering, the program has graduate students take a cross-school course curriculum and places them with a sponsor company. Students gain access to the program through a highly selective and competitive admissions policy, and are trained to "identify, discover, and translate into practice the critical factors that underlie world-class manufacturing."[12] The program is driven by the partner company, and though the LFM student has some freedom in selecting an area for contribution, the effort is based upon pre-defined areas of research, and not in entrepreneurial or hands-on project learning.

2.1.3 The LFM Knowledge Supply Chain Model

William Hanson of MIT Leaders for Manufacturing (LFM) Program addresses the situation of industry and academic partnerships by introducing the *knowledge supply chain*.[13] Likening the flow of knowledge and practice to the flow of materials in a physical supply chain, Hanson encourages a more continuous, two-way flow of information and knowledge from the source (research institutions) to the end user (customers, industry). The chain is summarized as:

> A knowledge supply chain is an integrated process that utilizes the core competencies of both industry and academia to provide the enterprise with the necessary knowledge to continually educate and train all its employees and associates. Given that a competitively skilled workforce depends on the continuous access to new knowledge as well as the efficient distribution of the knowledge, a knowledge supply chain will need to utilize and integrate the relevant research and knowledge generation processes of any industrial, academic or government institution.
>
> The output of a knowledge supply chain is a more effective and cost efficient knowledge process that ensures the manifestation of that knowledge in more effective people, and more competitive products and services.[14]

With a macro perspective of the industry-academia relationship, the knowledge supply chain principles recognize the inherent differences between the university and industry. In addition, an integrated knowledge supply chain recognizes the relationships that must be improved between traditional opposites:

- Industry and Academia

[12] "Leaders for Manufacturing, A Partnership for Change" program brochure, 1995.
[13] Hanson, William C. "The Knowledge Supply Chain. A Practical Tool from and for Industry/Academic Partnerships," MIT Leaders for Manufacturing. August 26, 1996.
[14] Hanson, William C. "The Knowledge Supply Chain" summary. MIT LFM. August 17, 1996.

- Technology and Management
- Research and Education
- Theory and Practice
- The Individual and the Institution

In order to achieve the goals of a more integrated system, MIT's LFM program is incorporating the supply chain concepts into its partnerships with industry. An example of a working prototype, the knowledge supply chain in this effort is still developing. Some of the benefits, however, include better prepared graduates for the partner companies, united MIT-industry efforts on industry-defined projects, and development of new programs for extended education.

Other efforts to more fully integrate knowledge supply chain concepts into industry-academia partnerships are encouraged, and in time the directed efforts hope to have the same type of benefits that the material supply chain had on manufacturing systems.

2.1.4 Awards & Recognition

As for other independent entrepreneurial endeavors, many activities at MIT are outside of the classroom. There are various contests which encourage, support and find promising inventors with marketing skills. These three are examples of such events:

- The Annual $50K Competition is one such contest, actually a series of progressively more demanding stages, which requires participants to submit a business plan about their particular invention, and to demonstrate the potential commercial value of the concept.

- The Lemelson-MIT Award presents $30,000 to a graduating senior or graduate student with inventive achievements. In 1995 and 1996, the award has been won by graduate students with extensive innovation experience and support, and who already hold pending and issued U.S. patents.

- The DeFlorez Award is presented annually to the team of undergraduates who demonstrate creative and effective execution of engineering projects which hold promise for additional development. This award also provides for a monetary award.

Third-party awards, such as the B.F. Goodrich Collegiate Inventors Program, are nationwide competitions that recognize and reward students for their inventions and innovation.

While these awards attract great attention and in doing so encourage others to follow suit and set high goals, these achievements may be considered as mostly benchmark rewards for those already involved in the design and development process. For those who need support to *enter* the process and who are *in* the process, students can look elsewhere.

2.1.5 Co-Curricular Activities & Support

Other activities, such as the Solar Car design program, offer alternative opportunities in design and engineering projects. Other programs give students the chance to work alongside members from other fields and communities to develop innovations or design solutions. Two such activities are briefly described here:

FIRST Tournaments

For Inspiration and Recognition of Science and Technology (FIRST), formerly known as US FIRST, holds a design competition each year. 1997 featured the fifth annual tournament in which teams made up of high school students, college engineering students and company engineers, design and build a machine to compete against other teams to achieve the game's objective. The contest, like that of MIT's 2.70 contest, involves design, fabrication, testing and modification of devices, culminating in competition when the robots and machines compete to outperform opponents. Significant portions of the development is guided by and conducted by the engineering students and by engineers.

Entrepreneurial Club

The Entrepreneurial Club and various smaller groups in the MIT community support inventive individuals. Through seminars and presentations, the individual can meet fellow innovators for information and discussion of their individual efforts, as well as meet potential partners in projects. The Technology Licensing Office is an on-campus center through which MIT-assigned inventions in research, technologies and intellectual rights are licensed, coordinated and protected. Non-university activities include the Inventors' Association of New England, another forum for inventors and aspiring innovators to meet and network. Meetings are held monthly.

2.2 Opportunities for Improvement

As the university environment changes, what existed before may not provide all that is needed for some students. While the foundations of an education are maintained, the remainder of the educational experience may be adjusted or realigned to better serve the differing needs and expectations of the ever-changing students.

2.2.1 Missing Factors in Current Programs

While the programs at MIT and other universities address the need for well-practiced engineering students, the changing means of educating those students, and the shortages in sponsorships and laboratory facilities, there still exist some weaknesses. These missing factors include:

- Facilitated resources beyond course timelines, including:
    - Materials
    - Manufacturing
    - Budget
    - Sponsorship
    - Consulting
    - Analysis
    - Time Availability
- Motivation beyond short-term rewards
- Continued project direction & management
- Development beyond mock-ups or simple prototypes
- An established network or correspondence with industry
- Business & financial planning
- Management of intellectual property

Are all of these factors necessary or sufficient for successful innovation? While there is no clear solution in the pursuit, identifying then providing for critical tasks in the process ensures that key tasks are not left unaddressed.

2.2.2 Depth Versus Breadth Models of Education

In design and initial development, the coursework and projects that students complete are indeed essential parts for future practicing engineers. Consider, however, a simplified illustration of the experiences and skills learned over time by a student in a hypothetical case. Fig. 2.2 depicts a hypothetical result of a student's education through project-based courses.

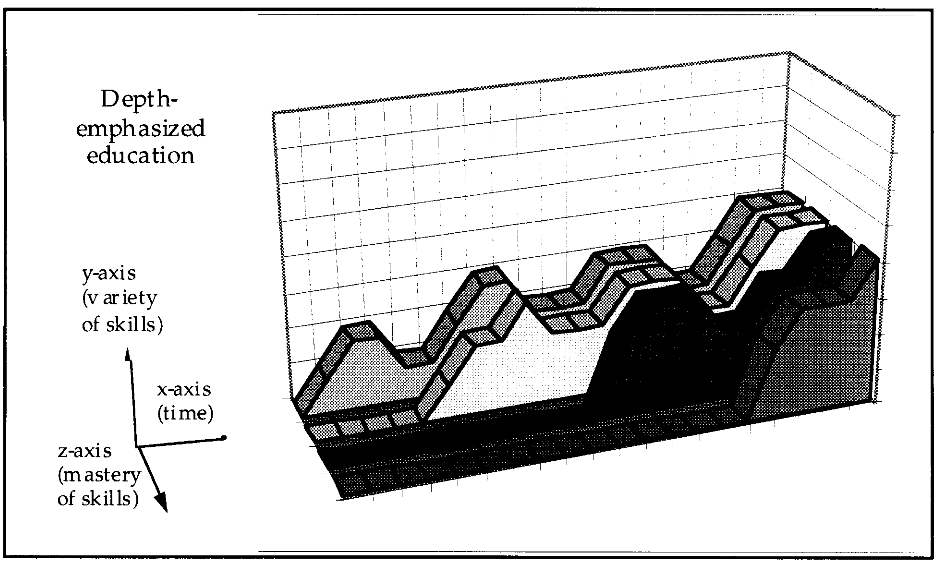

Fig. 2.2: A representation of depth-emphasized education. Each project (hill or hump) reinforces existing skills set, while breadth of skills set does not increase significantly.

The features of Fig. 2.2 represent progress as such:

- Each hill or hump represents a different project (e.g. a new course project each semester), beginning at the earlier steps of the design and development process.
- The curve moves upward as additional steps in the design and development process are learned as each project progresses.

- At the end of a project course, the peak drops off or declines, indicating the end of the course requirements and the corresponding work and interest by the student.
- Each additional project recounts steps already taken in other projects, thus building depth in those respects, but not necessarily progressing much further beyond them.

Time is represented along the x-axis; breadth and variety of skills are on the y-axis; depth or mastery of these skills is in the z-axis (out of page). In this model, the height of the curve does not increase significantly after numerous projects. Rather, the depth (y-direction) increases. However, the increases in the mastery decreases. This is based upon the hypothesis that the first or second experiences teach the student the most significant gains as compared to, say, a fourth project about the same principles.

Now consider the graph in Fig. 2.3, representing breadth-emphasized project education.

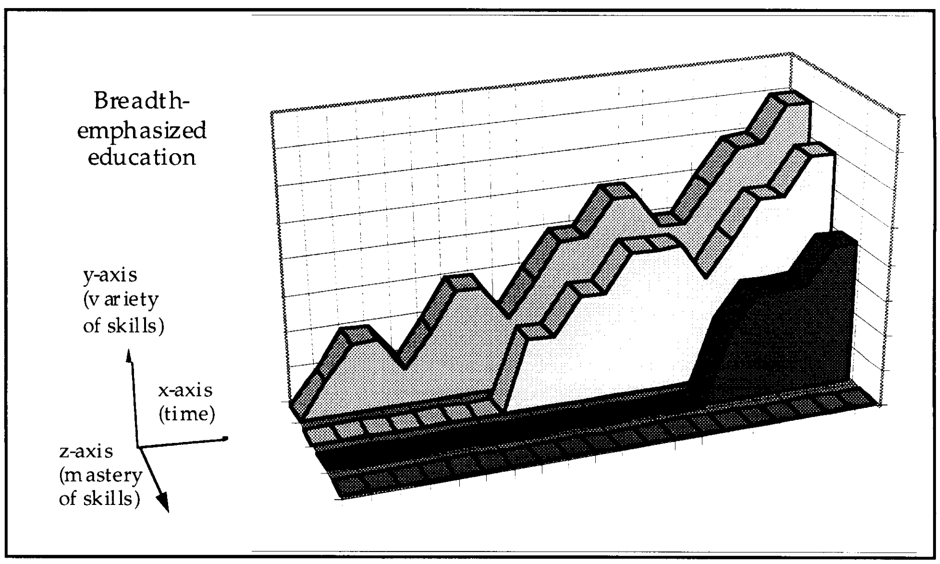

Fig. 2.3: A representation of breadth-emphasized education. As a major project progresses, it augments the skills set (height) from new experiences, while mastery (depth) of skills set may increase little.

Here, a different model is presented, representing fewer projects maintained over time:

- Fewer projects are undertaken, but are ongoing, not conforming to semester timelines.

- Over time, the y-height may undergo some decline, representing a student's reorganization of priorities with other responsibilities (e.g. exams, breaks), but regain height when the project is resumed.
- Depth (in z) may not increase substantially beyond the first one or two levels due to fewer projects reiterating those particular skills; however, the height in y continues to increase as other skills and concepts come into play (e.g. marketing, additional prototyping) and built upon previously emphasized abilities.

While these two models may be crude and oversimplified representations of engineering education, they serve to illustrate contrasting schools of thought: the depth-emphasized path versus the breadth of skills path. While there is no one best model for all students, it is hypothesized that the second model of progressively building skills may better suit students wanting and needing a broader collection of related experiences.

2.2.3 Islands of Education

It may be assumed that universities do a fair job in teaching the basics of a given field to their students over the course of four or five years, for standard bachelor degrees in mechanical engineering, for example. However, upon completion of their degrees, students entering the workforce may not be prepared for the design or engineering positions in which they find themselves.

How could this be, if the university has taught them the basics and some application of the concepts? Some students may graduate without having had significant opportunities to *apply* (as in "test-drive") their knowledge and understanding resulting in the skills required by industry. Unless activities and coursework can tie together the various theoretical and practical lessons with the greater picture of the business and real-world engineering realms, a university may only be providing *islands of education*. These islands of education can take the form of coursework, as solid and deep as they may be, which are not brought fully into practice by other means or coordinated with other coursework or lessons. Hence, the topics learned are isolated from others, and thus the way to fully utilize the knowledge, understanding and skills of those topics has not been illustrated for, nor participated by, the students.

Similarly, the lessons of developing a design into a marketable product can be scarce or ad-hoc in engineering schools,. While there may be business courses introducing product development from a management point of view, there may not be the in-depth start-to-finish explanation of the process of bringing an idea to market, including the subtle engineering nuances and details that can make or break a product. Case-studies help fill the gap between theory or guidelines and practice, but without actually executing or participating in such a project, much of the knowledge and understanding of the lesson may be lost.

The islands of education concept can be illustrated by representing each student curriculum's course or lab class as a small region in space. A number of courses, such as those taken in a particular department or division, is thus represented by several such entities in a larger region representing the greater field of knowledge. Each entity is separated from each other by varying distances, symbolizing the distinctions and commonalties between course material or emphasis.

For the field of mechanical engineering, for example, there would typically be a number of entities, each representing a different divisional subject or course. For other departments, such as business and management, a separate larger region would exist, with its own smaller entities representing the courses in that school. See Fig. 2.4 for an illustration.

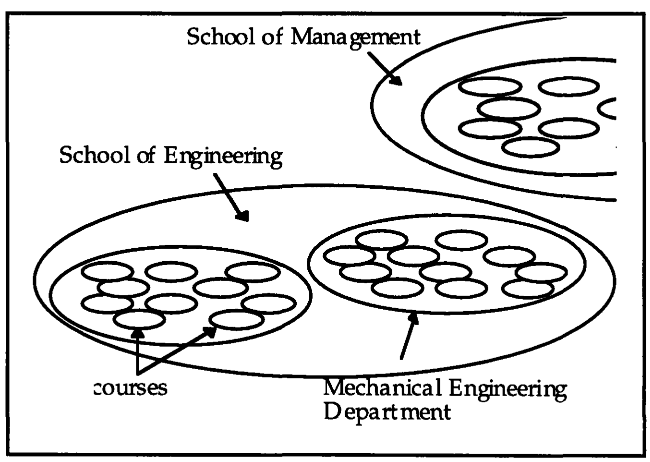

Fig. 2.4: A representation of university educational opportunities, by school, department and course divisions.

From this simplified picture, the domain appears as a scattershot distribution of entities, some close, but many distinct from one another. This distribution represents the so-called islands of education, suggesting that there often lacks a commonality that connects the islands to each other.

A standard university education might look like that in Fig. 2.5. With certain lab or project courses, there are some regions in the student's domain in which courses overlap and connect, thus representing topic reinforcement and continuity, respectively, between course material. However, the picture still shows a greater disjointed domain where coverage in the field does not exist.

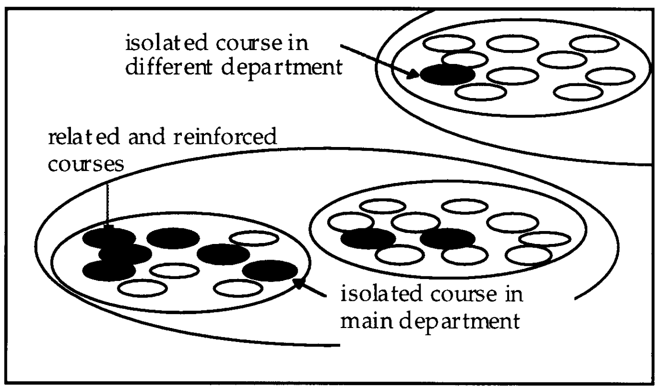

Fig. 2.5: A representation of a student's education. Filled circles represent courses taken. Related courses touch or overlap each other while isolated courses stand alone.

One of the consequences of taking distinct courses is that reinforcement (overlap) and connectivity (continuity) must be accomplished *after* the initial learning, whether by activities specifically for connection or by additional and partially redundant efforts. In addition, when considering coverage outside of the main department, the scarcity of entities and lack of connections increases, representing poor connectivity between the whole set of courses.

An alternate model of education involves a connected, growth pattern of courses. As illustrated in Fig. 2.6, several courses are initially taken, perhaps disjointed at first. Subsequently, additional coursework and academic activities overlap slightly but mostly *expand* the boundaries of each entity. At later stages, the initial domain covered by the first courses has grown to a more continuous field. Again, the keys to this kind of skill and experience coverage is through *reinforcement* and *connectivity* in education.

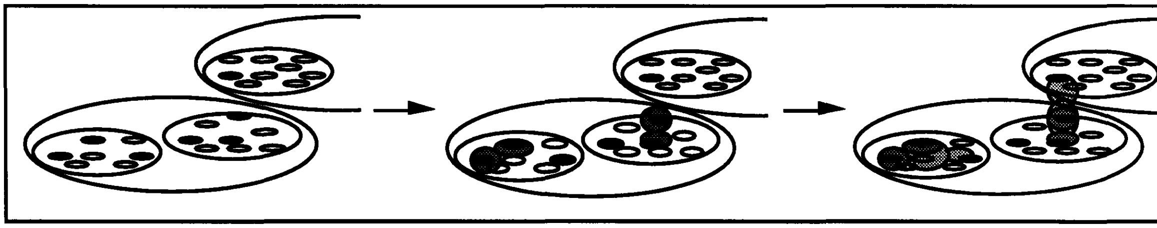

Fig. 2.6: A student's education with courses and activities that reinforce and expand upon other courses. In subsequent semesters, projects and courses build upon known skills and concepts. This type of reinforcement allows for dissimilar department subjects to be brought together in a cohesive manner.

In practice, it may be argued that each approach is as effective and efficient as the other in providing the comprehensive knowledge base to a student. However, when skills and experience are concerned, a better linked education in *processes* comes from the latter model for education, through A-to-Z learning, and longer-term projects, for example.

2.3 Motivation for Integrated Product Innovation Research

Giving the student the responsibility, and the opportunity and rewards, of design, development and marketing an original idea, Product Innovation Research serves to educate the innovative students by supporting their creative efforts. This kind of research is well-suited for design and engineering, where the fields themselves involve creativity and improvement and application of science to products and processes.

2.3.1 The Changing Environment of Education

Design courses, in which students are given a general problem statement and are allowed to exercise their creativity and innovation, are generally effective in overcoming an islands of education effect. Whether the work is independent, with one-on-one supervision or by teamwork, a key to success in the education of the students is the application of engineering and design principles to a real design problem, or at least representative of a real design problem. By applying the design process, from problem statement and need identification, to conceptual design, mockups and prototypes, these design courses provide a limited version of the design process as used or expected by firms, large or small. Learning by doing is a method of teaching design. Taken in the context of the "real" world demands, however, these courses still leave room for improvement.

There is also growing agreement that the "chalk talk" or the standard lecture alone is not highly suited for teaching skills that involve extensive designing and manufacturing and in teamwork. Since the nature of design and manufacturing can be so dependent upon the cooperation of colleagues and the use of hardware and tools, the standard lecture may not communicate or transmit key information that may be otherwise received by experimentation and testing. For example, a car engine can be explained on a blackboard, overhead projector, and through films and videos. However, to better appreciate the engine and the subtleties of it, students may learn more by disassembling an engine with on-the-spot instruction and demonstration. Furthermore, this instruction can then refer to prior coursework and theories to minimize the occurrence of the islands of education.

With the advent of the Internet and shared server access, basic lecture material can and is already being stored in digital form and accessed outside of the typical classroom. A good example is the material found in the World Wide Web pages for 2.007. Students already use the network to access administrative information, course changes, lessons updates and technical information about components used in the laboratory. While lectures are still given twice a week, much of the detailed information is available online, allowing instructors to shift attention to recitations and individual student instruction.

2.3.2 A Greater Student Motivator

A professor reflected upon students' motivations and objectives in their education:

> Surely, not all students accept passing the final as the sole objective of study, and few if any enter engineering with that in mind. But in reality, many are driven to that mode of learning in overcrowded curricula. There is ample evidence that many, if not most, carry little forward from one class to the next in an immediately useful form. Many instructors, even within the engineering sciences, find it necessary to repeat material thought to be previously learned to establish that it *is* of continuing importance before they are able to use it as a secure base for additional material.... It is not that they don't have the engineering science knowledge in an academic sense, but, rather, that they have never recognized it as having any value, let alone importance, beyond passing that last exam. That final exam, in a sense, is thought to free them from having to consider the material again. They lack the *wisdom* necessary to make original use of the knowledge. It has been said many times that one doesn't learn a subject until it is put to use. Apparently the necessary use must be

> something more useful, more demanding, and more personal than the structured, and seemingly terminal demonstration of understanding on a quiz.[15]

Again, two points stand out in this discussion of engineering education:

1. The carry-over of engineering material must be emphasized without excessive redundancy of concepts and principles.
2. Students must have greater motivation to put their education to use beyond quizzes and exams.

A provision of giving students a stake in the results of their educational activity, whether through equity or other incentive (financial, recognition or the like), may be a greater motivator for them to actively participate, contribute and learn than are grades and the more abstract notion of "educational benefit and preparedness." This stake can be a better reflection of the real world where return and payback are the norm. Another incentive can thus provide students otherwise motivated by the short-term exam another reason to maintain and value their education.

2.3.3 An Educational Opportunity

While central courses in engineering science in and of themselves may be well taught and well received by students, islands of education may still present difficulties when trying to integrate together various subjects and principles. Hence, *spanning* these islands is one way of improving effectiveness of any isolated subject matter. Recognizing the importance of industry and business practices as well, it seems appropriate to involve these societal or real-life subjects into the curriculum, if not by explicit lessons in official "active" courses, then by "passive" education. By "passive," it is meant that these skills be learned, perhaps independently by the students, in the process of some greater project or program of study. Already there are some example of educational activities which include "passive" learning. In 2.009, for example, large teams of students bring ideas to prototype, working models of various engineered projects. While teamwork, communication and management are all critical to the performance of the team, relatively little course time is spent actively teaching the skills.

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[15] Peterson, Carl R. "Engineering Education. A Focus on the Development of Wisdom" 1996. pg. 7-8.

Table T2.1 outlines a sampling of the different types of project-based activities and programs currently supported by the Department of Mechanical Engineering at MIT:

Course or Program	Timescale	Team size	Student selectivity	Typical skills involved	Supervision
2.72/2.721 (UG)	1-2 semesters	2-5+	required course	IG, ED, DD, MU, Pr, DFX, CI, MR	course instructors
2.009 (UG)	1 semester	~20-30	req'd	IG-Pr, DFX, CI, MR, CA	instructors, team leaders
UROP (UG)	1+ semester	1+	advisor approval	depends on project	faculty supervisor
Senior Thesis (UG)	1 semester	1-2	req'd	mainly eng/tech issues	faculty thesis advisor
Summer internships	summer term	1 + company sponsor	sponsor selection	depends on project; exposure to industry practices	company superior
2.739 (G)	1 semester	~4-8	elective course	IG-Pr, CI, MR, CA	instructor, team leader
2.74 (G)	1 semester	~3+ class team	elective course	IG-Pr, DFX, CI, MR	instructor
2.744 (G)	1 semester	~4-8	elective course	IG-MU, DFX, CI, MR	team peers, instructor
Master's Program	3+ semesters	1 + research group	graduate admissions, faculty placement	depends on project, mainly eng/tech issues	faculty advisor
New Products Program*	4 semesters	1 + company sponsor	program admissions	eng. & non-eng; involved w/ business practices	fac. advisor, company supervisor
LFM (w/ Sloan School)	4 semesters	1 + company sponsor	program admissions, sponsor selection	eng. & non-eng; involved w/ business practices	fac. advisor, company supervisor
Ph.D.	typically 3+ years	1 + research group	graduate admissions	depends on project; mainly eng/tech issues	faculty advisor

where: IG = Idea generation; ED = Embodiment Design; DD = Detailed Design; MU = Mock-Up; Pr = Prototype; DFX = Design-For-(various); CI = Customer Interaction; MR = Market Research; CA = Cost Analysis; * = now defunct

Table T2.1: Summary of some current MIT Mechanical Engineering project-based activities.

A review of Table T2.1 reveals an opportunity involving an intermediate timescale between two to four semesters, open to undergraduates and possibly continuing into graduate school, that more definitely incorporates non-technical experiences with a base of engineering and design work. Compared to current undergraduate activities, this longer timescale would allow for further development of projects, requiring more exposure to market and business issues beyond initial market research and customer interaction. Compared to graduate programs, this new opportunity need not require competitive admissions as advanced degree co-ops and internships are selective and limited in size.

Thus, the table above could include in the future another program that might look something like the following, in Table T2.2:

Course or Program	Timescale	Team size	Student selectivity	Typical skills involved	Supervision
Product Innovation Research	2-4 semesters	1 + support group	elective program	IG-Pr, DFX, CI, MR, CA, business, communications	fac. advisor, team supervisors

Table T2.2: Possible addition to project-based activities.

Of course, the skills involved and the supervision may be different depending upon the scope and expectations of the student in a program. In fact, the "program" could be another option, like a UROP, voluntary and not completely defined for all participants. Such alternatives will be discussed in following chapters. Nonetheless, there is an opportunity to reach out to students who want experiences similar to current activities but in a different structure and with more access to such a program. These activities could integrate coursework and passive education in a supported MIT effort to bring new opportunities to students, the university and participating industry sponsors.

Chapter 3

Product Innovation: Linking University and Industry Practices

In Chapter 2, the changing wants and needs of engineering students in the existing educational system have been discussed. How do we go about meeting those objectives of the student within the constraints and cultures of the university and industry? Whereas radical change may conflict too much, incremental change plus significant adjustment in key areas may be more practical and effective.

Considered in this chapter is the use of design and product innovation in the university system. Not only is product innovation the *object* of the activity, but the product innovation process may also be considered an *analogy* to the educational strategy. For example, in product development, there is the customer, the designers and the manufacturers. In the educational system, the student is the product, the professors are the designers, and the university is the manufacturer.

Thus, product design and innovation involve more than a mere physical object; rather, product innovation is a means of addressing concerns of educational and industry institutions, each with product and process issues of their own.

Section 1 discusses the challenges of teaching design and how industry practice may be incorporated into education. Section 2 looks at products and product development, identifying pitfalls to unsuccessful products in the marketplace. Section 3 relates the "completeness" of a product with a corresponding completeness of the student-engineer's skills set. Section 4 discusses the distinctions among institutions and individuals and identifies strengths of the university, student and industry that are essential to a networked activity. Section 5 presents a diagram scheme of classifying university-student-industry interactions and how each type may appear in the educational environment.

3.1 Reflecting Industry Forces in the University

Engineering and engineering design education is a difficult task in the university, as more and more concepts, both theoretical and practical, must be addressed. As students' desires for learning particular skills demanded by industry increases, this task becomes even more challenging.

3.1.1 The Nature of Design in Education

In many respects, design *is* creation. Depending on the context, "design" can be loosely interchanged with "innovation," as well. In some circles, the broad interpretation of "design" can also imply "engineering design" if not "engineering" as a whole. More broadly considered, design (as in concurrent design) can include manufacturing, marketing and sales issues and influences.

One definition sums up the enormity of the task: "Design is the bringing together of different fields, constraints, and ideas, for the creation and implementation of new and modified forms." This implies that design should include anything and everything, for the exclusion of an issue or concern is a missing piece of the ideal, perfect solution. Of course, universities cannot teach *everything*, just as students cannot absorb and understand everything, even if taught. Universities are challenged to teach the necessary parts as well as teach students to go beyond the basics and discover on their own. But if we have trouble defining the boundaries of "design," how then do we *teach* it?

Official definition aside, engineering design education may best include teaching the student *to learn, to think, to create*. Teaching can be done through telling, showing, involving, repeating, doing. The difference between engineering science and engineering science may come down to focus:

> There is a clear and appropriate difference between engineering science and engineering design teaching methods. It is a difference of focus: in the former the focus is on the mind of the instructor; in the latter it is on the mind of the student.[16]

Given that design is different from other sciences in that the student may not be able to fully simplify a problem into isolated, non-interacting subfields, practice and first-hand demonstration of the complexity of design are supported in university education. Through projects and laboratories, students can apply their scientific and engineering skills to an unstructured problem. They identify tasks and the often-conflicting constraints and necessities, and find solutions to satisfy the requirements as best as possible. Whether they call it optimization, engineering, science application or whatnot, this application of old to new is the ever elusive *design*.

As the field of design covers more and more material, such as design for manufacture, design for assembly, design for human use, etc., it is becoming clear that there is indeed much more to teach than a student can learn within the time constraints of a university education. Perhaps the university can provide more emphasis on creation — learning by doing — to complement the learning by other means.

3.1.2 Expectations by Industry

A recent study[17] revealed top practices identified by supervisors, engineering professors and working engineers of what new mechanical engineers need to know in the workplace. Divided by industry and academia rankings, Table T3.1 shows the top 10 practices identified by 80% or more of the participants as being "very important" or "somewhat important":

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[16] Ibid. pg. 5.
[17] *Integrating the Product Realization Process into the Undergraduate Curriculum*, ASME and the National Science Foundation; reported by Valenti, Michael. "Teaching Tomorrow's Engineers," *Mechanical Engineering*, July 1996. pg. 65-66.

Rank	Industry responses	Academia responses
1	Teams/Teamwork	Teams/Teamwork
2	Communications	Communications
3	Design for Manufacture	Creative Thinking
4	CAD Systems	Design Reviews
5	Professional Ethics	CAD Systems
6	Creative Thinking	Sketching/Drawing
7	Design for Performance	Professional Ethics
8	Design for Reliability	Design for Performance
9	Design for Safety	Design for Safety
10	Concurrent Engineering	Manufacturing Processes

Table T3.1: Top ten practices considered important by Industry and Academia.

While this study should not be taken as the final word on engineering education, or on engineering design education for that matter, it does raise concerns that subjects such as teamwork, communications, and "Design for X" must somehow be taught or learned in a curriculum addition to the mainstay subjects in engineering, such as materials, mechanics, dynamics, etc.

A response to this study might include the stance that without the fundamentals of engineering science, these so-called "soft" subjects would be of significantly less utility.

> Of what value, educational or practical, are such topics such as design for assembly, design for manufacture, life cycle design, robust product design, designing in large groups, and so on, if the student is as yet unable to effectively design for *function*? All are no doubt worthy subjects, but of little benefit at the undergraduate level if they are not built upon each individual's ability to design for function and work creatively and confidently at that foundation level.[18]

Nonetheless, expectations or desired qualifications by industry for starting engineers go beyond the basics of engineering. As the economy and the marketplace change and evolve, so too must the engineers in the workplace.

> The rise of small and midsize businesses has also been accompanied by a change in employer expectations of mechanical engineers. "Small and midsize companies want a systems individual," [Arthur Ebeling, ASME midwestern

[18] Peterson, Carl R. pg. 5.

> regional director] said. "They don't have teams of engineers, and they don't have specialists. They need one person who has the flexibility to do it all — all the way from idea to implementation.[19]

Even beyond the bachelor's degree, higher level graduates face the same situation. An industrial employer of advanced degree graduates remarked:

> Even the "best of the crop" take anywhere from 6 months to 2 years to become good, productive industrial researchers. Most recent graduates, particularly those who have not summer-interned, do not have the foggiest idea of what industrial research is all about. Some even think that using or developing technology to do something useful is not research and if it is a product that makes profit, is even slightly dishonorable.[20]

3.1.3 Augmenting the Learning Process

The above comments imply that the student should know more about industry and business practices as well as shoulder increasing loads of engineering science as those fields progress. By recognizing the constraints and function of a university curriculum, then, it seems a practical option that universities more efficiently support the *learning* process of the students if indeed the teaching resources are kept roughly constant. That is, one option for universities is to maintain the high standards of the mainstay coursework, of the *teaching* standards, while supporting students in their *learning* efforts, including learning the less definitive practices such as communications, business outreach, market research, customer interaction and concept integration.

Returning once again to implementing project-based programs to accomplish this integration of industry issues into a student's curriculum, Table T3.2 displays Tables T2.1 and T2.2 in a single outline.

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[19] Deitz, Dan. "Help Wanted: Engineers," *Mechanical Engineering*, August 1996. pg. 48.
[20] *Reshaping the Graduate Education of Scientists and Engineers.* pg. 184.

Course or Program	Timescale	Team size	Student selectivity	Typical skills involved	Supervision
2.72/2.721 (UG)	1-2 semesters	2-5+	required course	IG, ED, DD, MU, Pr, DFX, CI, MR	course instructors
2.009 (UG)	1 semester	~20-30	req'd	IG-Pr, DFX, CI, MR, CA	instructors, team leaders
UROP (UG)	1+ semester	1+	advisor approval	depends on project	faculty supervisor
Senior Thesis (UG)	1 semester	1-2	req'd	mainly eng/tech issues	faculty thesis advisor
Summer internships	summer term	1 + company sponsor	sponsor selection	depends on project; exposure to industry practices	company superior
2.739 (G)	1 semester	~4-8	elective course	IG-Pr, CI, MR, CA	instructor, team leader
2.74 (G)	1 semester	~3+ class team	elective course	IG-Pr, DFX, CI, MR	instructor
2.744 (G)	1 semester	~4-8	elective course	IG-MU, DFX, CI, MR	team peers, instructor
Product Innovation Research	*2-4 semesters*	*1 or more + support group*	*elective program*	*IG-Pr, DFX, CI, MR, CA, business, communications*	*fac. advisor, team supervisors*
Master's Program	3+ semesters	1 + research group	graduate admissions, faculty placement	depends on project, mainly eng/tech issues	faculty advisor
New Products Program*	4 semesters	1 + company sponsor	program admissions	eng. & non-eng; involved w/ business practices	fac. advisor, company supervisor
LFM (w/ Sloan School)	4 semesters	1 + company sponsor	program admissions, sponsor selection	eng. & non-eng; involved w/ business practices	fac. advisor, company supervisor
Ph.D.	typically 3+ years	1 + research group	graduate admissions	depends on project; mainly eng/tech issues	faculty advisor

where: IG = Idea Generation; ED = Embodiment Design; DD = Detailed Design; MU = Mock-Up; Pr = Prototype; DFX = Design-For-(various); CI = Customer Interaction; MR = Market Research; CA = Cost Analysis; * = now defunct

Table T3.2: Summary of many of MIT Mechanical Engineering's project-based courses and programs, with the addition of a proposed Product Innovation Research Program.

To reflect what is taught versus what additional skills must be learned, a Product Innovation Research Program might be subdivided into what is taught by instructors versus what should be learned by the students in the activity:

- Taught: methods of Idea Generation through Prototyping, Design-for-(various practices); guidelines for Customer Interaction, Market Research, Cost Analysis
- Learned: Business Practice, Market Research, Patent Research, Communications, Sales

3.2 New Products from Innovations and Inventions

Why pay attention to new products? In the global marketplace, new products make up a large portion of companies' sales, and each year new or modified models, features and capabilities can be found on the market. Hence, it is becoming more important for industry to better understand how to make a better product, and to hire employees who can effectively execute the making of these products. Without that understanding, there are likely to be voids in development and marketing tasks, hurting the product's chances for being successful.

For individuals or small firms, the chances of product success can be slim, if not approaching impossible, due to lack of resources or other obstacles.[21] Even for large corporations, introducing new products requires incredible efforts by all areas of an organization, from designers to marketing to sales to service. Some companies can spend tens of millions of dollars to introduce a new product.[22]

As for student and university involvement with new products, it is logical that course projects and laboratories in a design curriculum should emphasize the development of new products. Indeed, universities already require their engineering students to design better products based upon real world problems and demands. However, as real world products involve more than just the technical considerations, design education may need to address more than the classic engineering aspects. Thus, when students graduate they will be ready to be productive members of a new product team.

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[21] Lectures by Rines, R. MIT Course 6.391 Development of Inventions and Creative Ideas, Spring Semester, 1996.
[22] In "Winning at New Products" by R.G. Cooper, it is stated that it costs Proctor & Gamble $100 million to introduce a new brand in the United States.

3.2.1 More Than a Good Idea

A dictionary defines "invent" as "to conceive of or devise first; originate."[23] Similarly, "innovate" is defined as "to begin or introduce (something new)" and "to be creative." The patent laws, of the United States and of countries abroad, define in legal terms an invention in numerous ways, with many subtleties and connotations. Generally speaking, most products on the market, whether consumer or technical or otherwise, were "invented" by someone or a group of people, and these inventions were further developed and marketed to customers. However, whether or not a "new" product is entirely new in the inventive or innovative sense, or merely a new package of prior known ideas, is not the only factor in determining the value, worth or utility of a product or item. In fact, a successful product relies on more than an ingenious or clever idea; issues such as ergonomics, economics and even societal expectations or biases can damn even the "best ideas." Hence, it can be said that *"Good products are more than only good ideas."* As discussed in terms of complementary assets[24], product success may also depend on marketing, distribution, service, intellectual property protection and the like.

In the process of transforming an idea into a real product, and given this statement, the purpose of *product development* in this context is to give form and detail to the idea, a possibly vague or general notion of an object or process, for example. *Product marketing* in the idea-to-shelf context, is the business, advertising, communication and selling of the product. Without development or marketing, the chances of an invention becoming a commercial success decreases significantly.

Let us consider a children's toy that is familiar by adults and children alike: the Lego™ block. Although Lego™ brand toys first became popular in the 1960's and continues as an industry "legend" into the 1990's, the particular "toy building brick" concept upon which the modern toy construction sets were built was submitted for a U.S. Patent in 1958 and issued in 1961. What happened between 1958 and the first series of toy sets involved product development and marketing.

Continuing with the building block example, consider the various features of the toy construction sets. Undoubtedly, this "simple" invention transformed into a mainstay of

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[23] *The Concise American Heritage Dictionary*, Revised Edition; Houghton Mifflin Company, 1987.
[24] as discussed in MIT course 15.351 Management of Technological Innovation, Sloan School of Management, Fall 1996.

children's toys and educational tools today. In order for this to be achieved, however, the company in possession of the toy building block patent concerned itself with numerous issues including the following: versatile, interchangeable and modular design; strong and rugged properties; variety of shapes, colors and block elements; affordable to the producer, retailer and consumer; precision manufacturing; legal concerns and patent protection; marketing strategy and business planning. From this short list alone, it can be seen that success depends upon more than having a novel concept.

From this and other examples of ideas and products, two hypotheses are made about invention success.

> 1) Innovations draw from and then catalyze efforts in business, education, technology and society.
>
> 2) Proper design of a *Design-Development-Marketing (DDM) Network* is essential.

The first hypothesis notes that ideas are so-called islands unto themselves until outside stimuli and issues are considered and incorporated into the growing concept so that a product (whether it be a machine, process, material or otherwise) is "in tune" with the environment in which it is to be a part of. These stimuli are the business, educational, societal and technological (BEST) realms. That is, a toy idea needs to be considered in the realm of its intended marketplace, the children's environment. For example, a toy should be safe for children, rugged against physical misuse, and yet attractive to the children, and hopefully educational. Without incorporating these features into a toy, it is less likely that the toy concept will find a place in the children's market. Considering safety standards and liability concerns central to the business side of a product, these *desired* characteristics of the toy make the same characteristics *necessary*. The same coordination of business, education, society and technology applies to products and innovations.

The first hypothesis asserts that innovations then catalyze further work into the four BEST areas. For example, in the Lego™ case, precision manufacturing of the tooling required to produce the injection molded shapes as well as the plastic compounds used for the toy blocks were developed in the years during and after the submission of the application for a patent. The plastics and manufacturing industries, although existent and flourishing, continued development of its tooling and material technologies, in part by the demand for more cost-effective progress. The impact the toy sets had on the children's education, while difficult to quantify, is similarly significant. Hence, innovations also return the stimuli to the BEST realms. This interaction is diagrammed in Fig. 3.1.

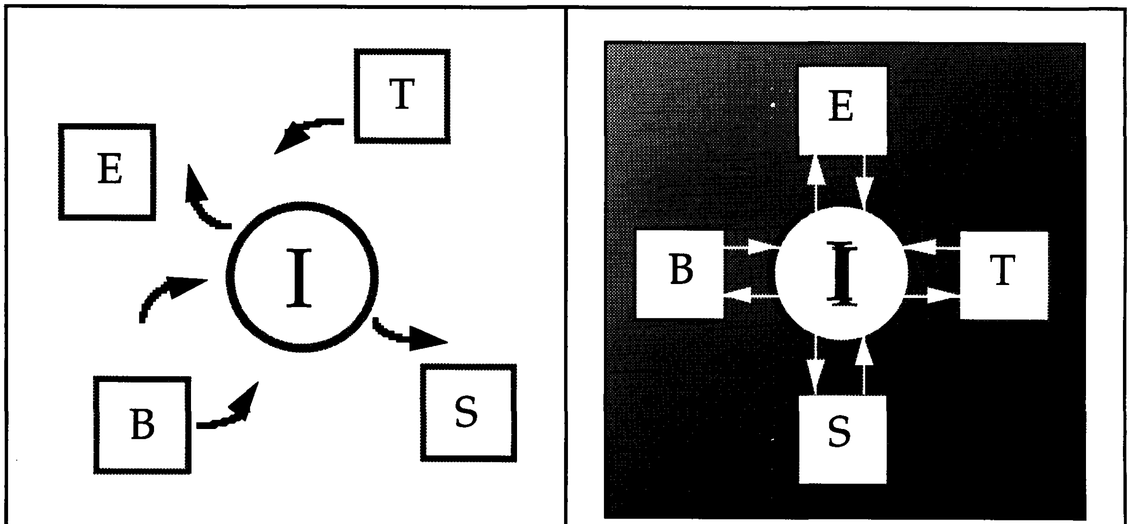

Fig. 3.1a: Poor BEST Integration

Fig. 3.1b: Proper BEST Integration

Fig. 3.1a: Without incorporating Business, Educational, Societal or Technological issues or practices, Innovation attempts can be poorly executed; Fig. 3.1b: A properly designed Design-Development-Marketing Network draws from and returns contributions to the BEST realms.

The second hypothesis asserts that to increase the opportunity for an idea to become a product, a network to encourage and support design, development and marketing activities is vital towards achieving innovation success. Current activities such as inventor clubs and associations are similar in purpose. These organizations, such as the Inventors' Association of New England, meet regularly and bring together individuals who help one another in patent applications, invention development and marketing efforts.

However, as will be discussed in a subsequent section, often these current networks lack certain features or resources that are necessary for consistent design, development and marketing of product ideas. The very fragmentation of all these resources (islands of education) mirrors the problem of fragmented results: activity must move from separate information entities to a united innovative effort. While current associations can be of great help to those starting out on ventures, there are other ways to design a DDM network in certain communities. Later a DDM network incorporating the university setting will be proposed.

3.2.2 Obstacles to Success

Considering how complex the processes of inventing, patenting, developing and marketing can be, it should not be surprising how many reasons are cited as to why inventions do not become successful. Among these obstacles, listed in no particular order:

1. Poor product design
2. Poor market research
3. No means of analysis
4. No means of prototyping
5. Lack of reputation with industry
6. Limited human resources
7. No capital

These reasons for low success should not seem surprising. Notice that they also involve the four BEST areas.

The first obstacle listed is *poor product design*. Product design involves numerous issues such as ergonomics and human factors, design-for-manufacturing, design-for-assembly, lifetime and safety. While product design can be interpreted in various ways, in this context it is to mean the physical embodiment and the features and functions associated with the actual output, or product. For example, is the product too big, or too small? Too light or too heavy? Although these judgments are subjective and difficult to quantify or generalize, it is often simple to identify bad or poor design for any given object or product.

This leads to the second listed obstacle to success: *poor market research*. Will anyone like this product? Will customers pay how much for what? How much is a patented idea worth to a potential licensee? Market research identifies the previous and existing markets, and the areas of sales in which the product will be carried and advertised. Failure to heed the trends and signals of a market or industry means that perceptions of a product's value or worth can be seriously mistaken or wrong. Careful market research can inform a product's company how many potential customers in a region exist, how much they spend on similar products, and in general how much interest there is or will be for a product of a given nature.

The third obstacle is related to the first two. *Analysis,* both in engineering and marketing, is a way to determine the expected performance of a given design and to identify potential weaknesses in a given design, compared to any existing designs. These areas of weakness can then be eliminated or improved upon as a result of the analysis. A product made without proper analysis can have serious failures or flaws, which can then lead to loss of work, resources and health in some cases. Also, when analysis is done, showing good results, this same evidence can then be used as a selling point to potential customers, showing proof of worthiness and functionality to the intended audience.

Prototyping, like analysis, is also essential to the DDM process. A prototype is a simulation of the intended end product result. In product prototypes, the object should have the look and feel of the end product, and should be as functionally similar as possible. A proper prototype provides the designers with a tool from which they can improve the design by learning about the strengths and weaknesses of the current design. This feedback can be gained from not only the designers themselves, but from user focus groups, people who know little about the details of making the device or object, but are like the intended users and maintainers of the invention. Also, from the marketing point of view, a prototype provides an audience with a close representation in physical form of the intended product so that they, too, may gain a better understanding of the product concept.

Lack of reputation with industry is cited by many as a frustrating obstacle towards marketing an idea. While an idea may be feasible or genuinely valuable, communicating that notion to a company or buyer may be difficult. One reason is that the company or buyer often has suspicions about the seller. Is the product idea a valid one or poorly-formed nonsense? Does the seller know what the industry requires? A well-recognized and positively-received company name, for example, more likely pass through initial suspicion. Just as a well-developed resume allows applicants to enter the job search with an advantage, a positive reputation with the intended industry is a desired characteristic for marketing a product or concept.

Without the appropriate people or without enough qualified participants, product development and marketing can be next to impossible. While an individual or small group of people may have the skills and resources to develop a product, there are other activities which require more people than the designers themselves. This *lack of human resources* partially involves market research and user focus groups; without people testing the product or prototypes, valuable feedback for design improvements may not be gained. Also, when individual or small group efforts are not enough for the design, analysis or prototyping efforts, other people may be needed to assist or completely execute the required activities.

One of the most significant obstacles to launching a new product by an individual or small group or even a company is *limited capital or finances*. Typically most steps in bringing an idea into the market cost money, up front without guarantee of a return. A patent application can be costly (for patent office fees, and usually legal fees); design and development involves cost of resources; marketing involves communication costs. How does an inventor afford the entrepreneurial efforts? There are several ways a product can be funded, including loans, venture capital, licensing agreements, and personal contributions. Generally, the more capital raised up front from outside sources, the lower the equity retained by the inventor; the more risk accepted by the inventor, the greater the potential payoffs, if any. Often the inventor may "sell out" to a venture capitalist or company in order to see through a product idea but only to lose most control over the end result, or an inventor takes huge financial and sometimes personal risk, sometimes to never regain a fraction of the investment. Sometimes, the product idea is simply abandoned for financial hardships.

Even before large-scale production costs come into play, the design and development of a product may lead to financial difficulty. Sending drawings or designs out for analysis or optimization, for example, can be expensive. Perhaps even more limiting is the time-cost equivalent, the notion that the time spent on one project takes time and thus earning potential away from another. In cases where an invention is developed in someone's "spare time" it is difficult to maintain such efforts while supporting one's self in a full time job. The other extreme is devoting all of one's time to an invention and its development without a steady source of income. And all the while personal responsibilities such as family can be important influences and factors. How can an inventor do all, work and develop an invention, and without giving up his equity to a third-party, and while maintaining an appropriate home- and domestic front? Thus, the innovation process is a continuing balance or trade-off of maximizing potential while minimizing risk.

3.3 Relating Actions and Abilities to Product Potential

The phrase "You are what you eat" has usually implied that a person's health is directly affected by the quality of diet. More generally interpreted beyond food and health: the quality of output is directly correlated to the quality of input. In the context of this thesis, it is hypothesized that there is a necessary relationship between students' skill sets and the condition of what they produce with those skill sets. Additionally, any shortcoming in an educational system may manifest itself in a correlated shortcoming in the product, where "product" can be taken as the physical item or object produced by the engineer as well as the engineer. Learning through product development can allow for better products in the future.

3.3.1 Product "Completeness"

Consider Fig. 3.2, showing a representation of a product concept. It is shown as a function on a domain consisting of three overlapping regions, representing, for example, customer demand, value and quality, or perhaps market presence, costs and technological level. Whatever the exact region label, these regions reflect the business, education, and technology categories (B, E and T of the BEST realms) of a product's or product idea's "completeness."

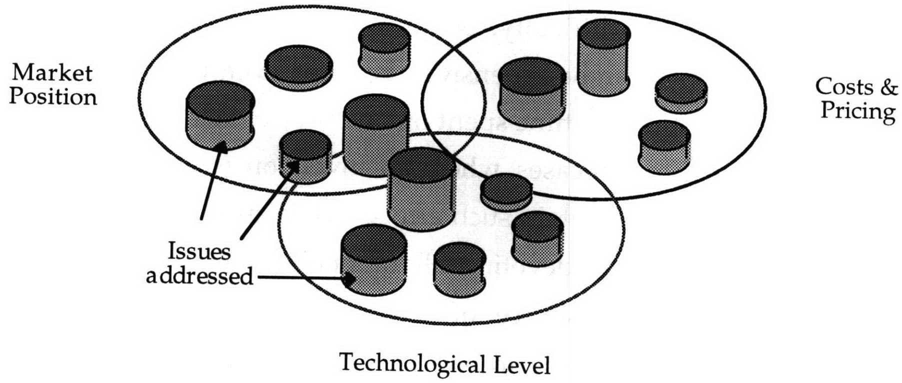

Fig. 3.2: A product's "completeness" can be illustrated by the number of areas covered (cylinders) and by those areas' strengths (height of cylinders).

For a given product concept, within these regions, the issues which have been addressed and included within the product content are indicated by a built-up volume about the domain. The more issues addressed, the greater span or coverage over the domains. The greater an issue is satisfied, the deeper the build-up. The greater the volume, the greater the chances of the product being a market success. While there is no established threshold or critical volume for guaranteed success, the more "complete" a product (via its mapping) the greater the potential.

3.3.2 Student "Completeness"

Now consider Fig. 3.3, a mapping of a student's or engineer's "completeness." Notice that the general form is the same as the product concept's model. Three regions in the domain are identified. For example, in this figure, they are: business and market exposure; education and background; knowledge and ideas. For those individuals attempting to function in work environments involving these areas, those workers with more "complete" mappings will have a better chance of succeeding in the tasks.

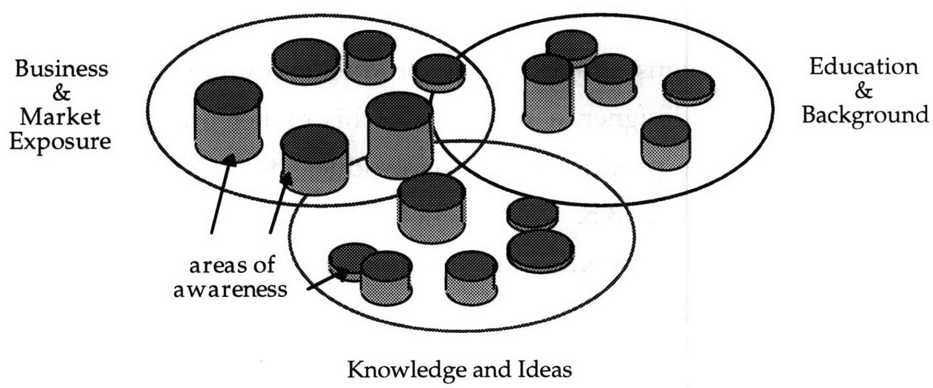

Fig. 3.3: A student's or engineer's "completeness" can also be represented by the number of qualifications (cylinders) and by those qualifications' strengths (height of cylinders).

Note that the earlier representations of depth- and breadth-emphasis education and the concepts of islands of education can both be represented by these cylinder completeness mappings. Fig. 3.4 illustrate how mastery and skills set size (graph depth and breadth) correspond to regional completeness (cylinder height and diameter).

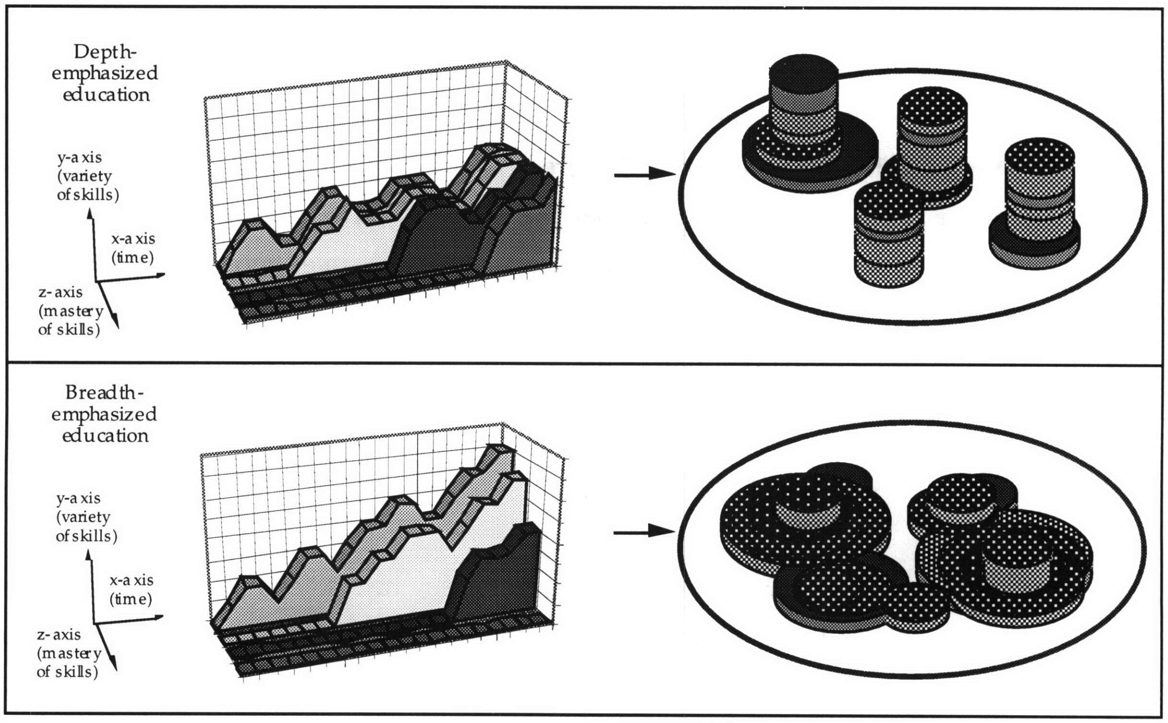

Fig. 3.4: The differences in depth- versus breadth-emphasis models for education can also be represented by the "completeness" representation.

3.3.3 Student-Product Correlation

A product developer designs products; the product's completeness will reflect the actions and tasks of the designer, a reflection of his or her own skills completeness. Thus, the mapping of the product with the product designer are at least loosely correlated, as shown in Fig. 3.5. While not necessarily a one-to-one functional relationship, the relevance of a product to its originator cannot be ignored: the better the designer/developer, the more likely the better the product.

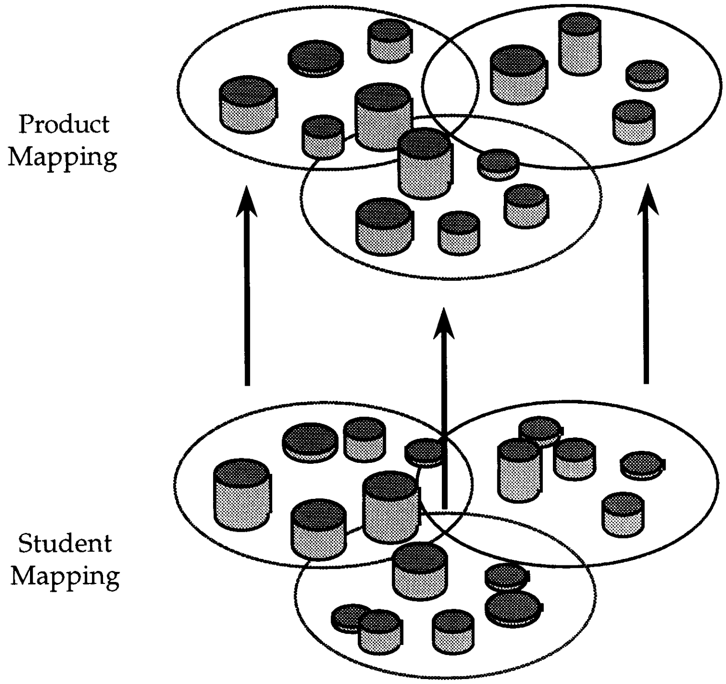

Fig. 3.5: A product's "completeness" mapping is correlated to the completeness mapping of the product innovator or developer. While not necessarily a one-to-one transformation, strengths in one mapping are generally related to strengths in the other.

It seems fitting, then, to use product innovation as a medium to build up the engineer's or student's completeness. Not for the person to merely reproduce a particular object over and over again in the future, but to serve as a *model process* for the person to follow. Rather than use a scattershot approach to preparation, possibly resulting in the islands of education which in turn can lead to scattershot results, why not overcome the islands through connected and reinforced education that can result in more complete products (both object and student)? That is, as Fig. 3.6 represents, a more complete innovator is more likely to produce more complete innovations.

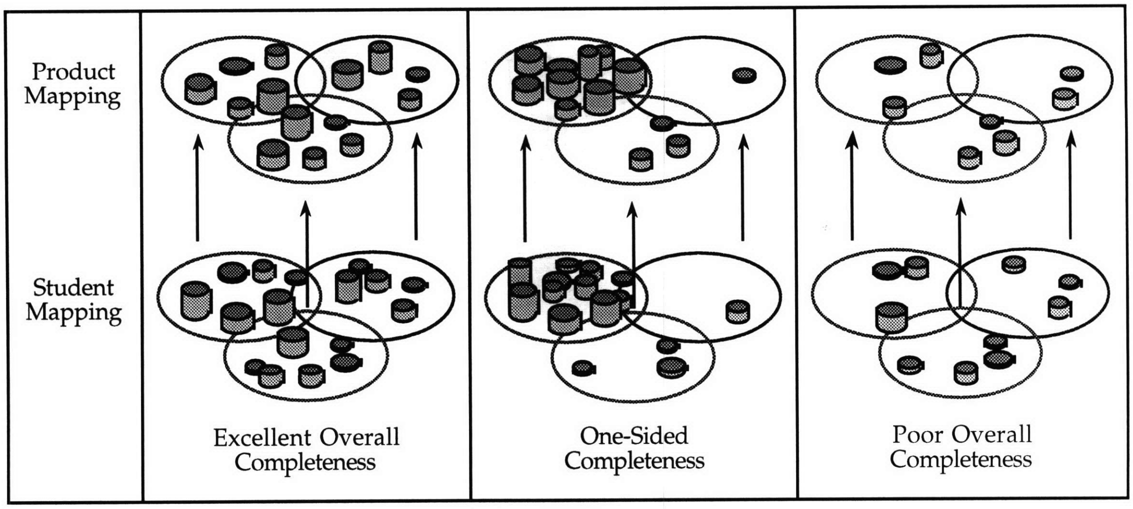

Fig. 3.6: Product and designer completeness mappings can show various states. Excellent overall qualities have entities in all regions; one-sided mappings are more heavily filled in one region only; poor mappings are sparse in all regions. Products having excellent qualities are generally more likely to be a success as opposed to those with poor quality coverage.

While this may all seem obvious and already implemented in various forms in universities, a closer look reveals areas for adjustment. This does not mean that universities should teach students to make a widget and only a widget, but to encourage them to generalize beyond the original embodiment, widget or not, to apply towards new and improved applications, just as schools expect students to generalize other scientific principles beyond the specific exercises and problem sets. This encouragement and support can be furthered in engineering education, beyond discrete tasks and limited projects, and into experiencing more realistic terms.

3.4 Individuals and Institutions

The Institutions of the University and Industry are centers of resources: human, material and information. The balances and specific portfolios of these resources differ, as well as their implementation and use. For the purpose of partnerships in a university setting, particular aspects of one institution integrated with aspects of the other need to be chosen wisely to maximize the total effectiveness of those activities.

The individuals involved, namely the students, cannot be overlooked. As the students are the ones conducting the research and designing and developing the products, they cannot and should not be neglected in the coordination and implementation of a collaborative effort – the students should be empowered to run the project, and not simply left to follow a pre-ordained syllabus.

3.4.1 Strengths of the University and Industry

The university is a center for research and education. Simply stated, the faculty teach and guide the students, and the faculty and the students conduct research. Within its culture, popularized as a free-thinking, few-constraints arena for investigation and discovery, are *creative human resources.* While the stereotype of the long-haired, unkempt researcher holed up in a laboratory is excessive and exaggerated, but the basic notion holds true: the university type is a creative thinker pushing the boundaries of what is known and possible, breaking the limits of what was thought was impossible, in theory and in practice. This spirit and curiosity applies to the students as well as to the faculty. The co-location of these human resources is a major cornerstone of the university system, and the built-in community of the faculty and students makes the transfer and discussion of science and technology that much more dynamic.

Universities benefit from the material resources not available elsewhere. Often the origin of cutting-edge fundamental research and applications such as computer-related systems and engineering breakthroughs, the university maintains and implements leading computer facilities, analysis and testing laboratories, and new experimental systems. MIT has a school-wide computer system available 24-hours a day to all faculty and students, with access to various applications and programs, Internet service, and telecommunication options as well. Within the school of engineering, MIT also boasts multiple laboratories for mechanical engineering, design, manufacturing, electronics and cross-disciplinary research.

A third strength, to complement the co-location of human resources and material resources, is information. Libraries, general and discipline-specific, as well as research groups' own collections, hold information in print. With the ubiquitous computer system on university campuses, access to digitally-stored and up-to-date information certainly expands the university's information resource.

Industry, in comparison, yields a different set of strengths. This includes human resources focused on the application and modification of technology for different customers. The emphasis is often less on fundamental research and more on repeatable, efficient implementation of developed concepts, for a larger market effect. Hence, its human resources are different from that of the university, and as such are bound by different rules and constraints. Less free to conduct research for the sake of discovery, industry is often limited by its responsibilities to its market and its customers. But in doing so, the effects of their actions reach the individual faster and in a more usable form.

Material resources are generally also larger-scale. The tools for analysis and production, for example, are geared for higher-volumes , faster speed and lower costs. With the vast array of companies and enterprises in countless industries, the spectrum of what can be materially produced exceeds that which universities can do. For instance, while a university can model and optimize the use of a particular material in a process, it is industry which holds the resources to actually produce the object in significant scale.

This last point leads to another key difference between industry and university strengths: funding. Industry as a whole spends much more on research in actual dollars than can the university. The buying power of industry shadows that of the university, and represents an area where contributions and partnerships with universities can be investigated.

3.4.2 A Collective Approach to Innovation and Education

Given that the individuals and institutions have different abilities, expectations and pressures, it may be difficult or inadvisable to attempt a collective activity. However, the optimistic view, and a practical view, is that this diversity is an asset and opportunity.

How does collaboration between the university and industry work? Ideally, each institution contributes its strengths and shares its resources to the effort. The university can provide its unique balance of human, material and information resources, while industry contributes its own distinct set of human, material and financial resources, and in the end the results are beneficial to each institution.

Not to be lost in this discussion is the role of the students. While the goal of a student is to learn, the student also contributes to the research conducted by universities and industry partners. In fact, undergraduate and graduate researchers ("students" in name, "workers" as well), are central to these efforts. No university effort should be without the participation, input and welfare of its students.

Students are inherently different from practicing engineers and researchers. Not bound by the same constraints of industry employees, for example, their culture is much different, as affected by the university culture in which they function. Generally speaking, university design work, for example, is less constrained by budgetary and time demands compared to industry, working hours are not confined to "9-to-5" standards, and "failure", or fear of failure, has different meanings and implications to the student.

These differences and strengths are considered for the proposed Product Innovation Research Program for Education. Students working on their own product innovations, with contact with university resources as well as industry support, would be learning through a new medium in a more realistic work environment, but with the same standards for education and rewards for performance. A networked activity with the university, students and industry would:

- Provide students the means to develop ideas beyond paper-designs, mock-ups and simple prototypes.
- Improve student access to manufacturing, testing, patenting, licensing of products through industry participation.
- Augment university efforts to teach real-world skills to undergraduate and graduate engineering students.
- Encourage small-firm organization by motivated young professionals.

The collective university-student-industry effort based in the university would differ from a standard activity in several ways, including:

- Easy access to numerous fields of expertise is built into the university system.
- University design work is less constrained, more "free-flowing" and generally uninhibited.

- Highly-motivated, creative students can operate without "9-to-5" concerns.
- Failure in industry can be more personally detrimental.
- Worst-case scenario for the university is that the students learn.
- Industry can introduce its perspective in the education of potential future workers.

Not to be left out is the personal motivation that students gain from having a stake in the project. The innovation and the development of the product become the students' "baby," a personal responsibility and opportunity to follow through and maintain. Knowing that the success of the project depends greatly on the students' motivation and dedication, and with potential capitalistic gains, student innovators contribute a more earnest effort.

3.4.3 Benefits to Participants

Why would the participants want to be involved in such activity? These projects could offer unique benefits:

Students receive:

- Design, development, and market education
- More individual interaction with working professionals and faculty
- Patent and business opportunities
- Financial rewards (e.g. royalties)
- Improved preparation for post-graduation roles

The university receives:

- Project funding from sponsors
- Endowments, royalties
- Publicity for itself and its programs
- Another means to involve its students and faculty

Industry participants receive:

- Access to new products and processes
- A head start in research and development
- Potential marketshare from new products

- Access to motivated students for future employment

Some of these benefits may result from programs and activities currently implemented at universities. However, other options involving university and industry partners are available and need to be investigated further.

3.5 Classifying University-Student-Industry Interactions

Given the distinctions among the university and industry in their resources and cultures, organizing activities including both realms requires careful consideration. Where such directed efforts or programs involve students, these interactions can take on various forms. These numerous university-student-industry interactions, or "USI Models" for short, can be illustrated in simple diagrams to represent the forms currently implemented, as well as those not yet supported.

Fig. 3.7 shows five types of USI Models, **I** through **V**. The three main participants in these activities are the student, the university and industry. How these three entities overlap, or interact, varies depending upon the type of cross-communication and interdependence. Also represented are students' colleagues and new organizations as they occur.

- Type **I** is the Independent Model, where the three "participants" do not interact much at all, and the student performs work with little guidance from the university or industry environment.
- Type **II** Models are those typical of university educational and research programs, in which students are exposed to varying degrees to industry practice or issues, but within an educational context.
- Type **III** Models take on a more student-independent slant, whether or not the university and industry representatives have previously been collaborating.
- Type **IV** Models take those models one step further by recognizing the formation of a new entities by students and colleagues from Type **III** activities.
- Type **V** Models are work models, representing the activities undertaken by the graduated student.

Type **I**, **II**, and **V** Models are more easily recognizable as they are represented in current university and industry environments. Type **III** and **IV** Models are not widely implemented and thus represent alternatives to existing university-industry activities involving students.

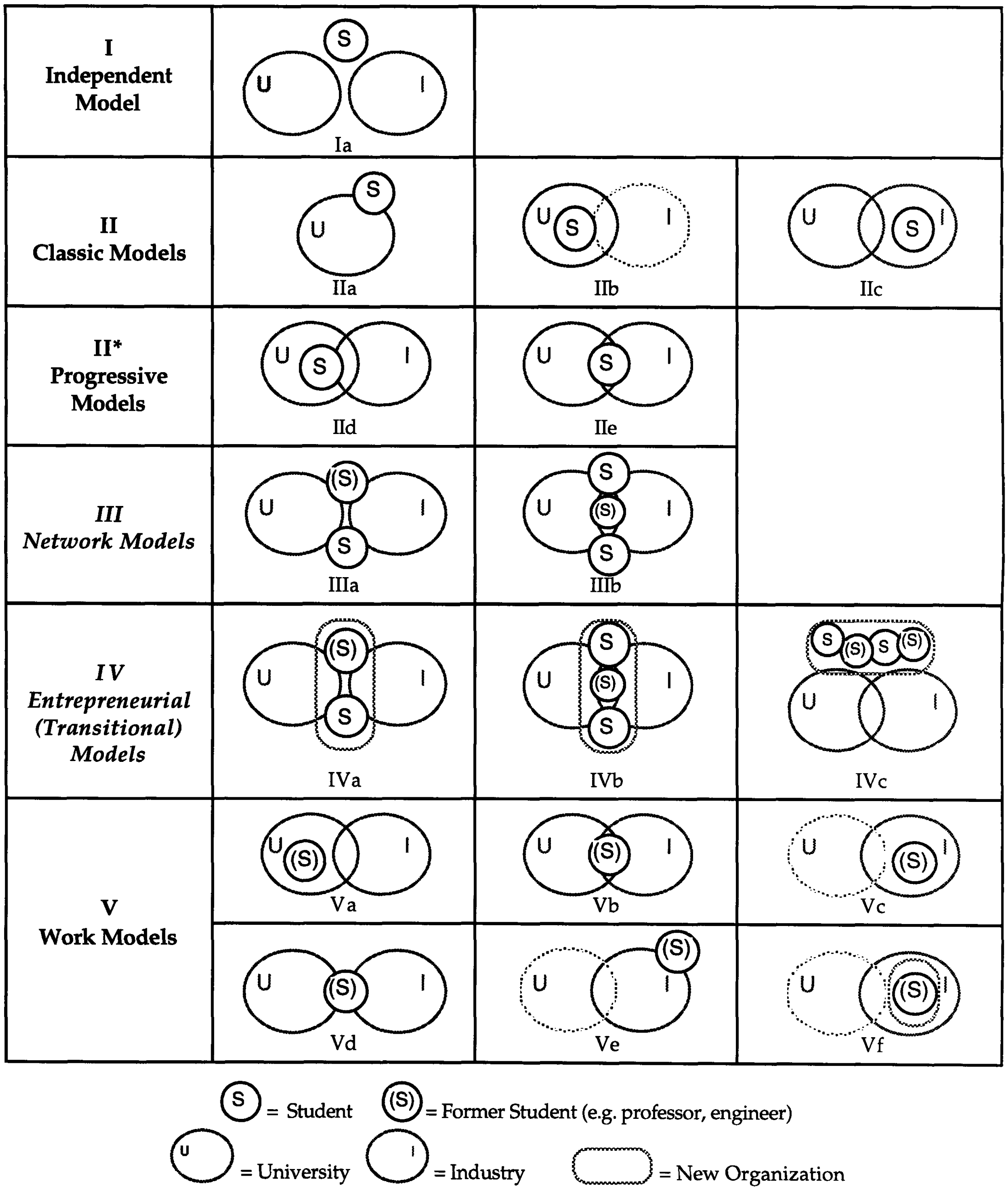

Fig. 3.7: Diagrams of University-Student-Industry relationships. Overlapping entities represent a sharing or transferal of information, resources and issues. Types III and IV are not yet common.

3.5.1 Type I: Independent Model

The Type I Independent Model (Ia) is shown in Fig. 3.8 as three non-overlapping regions. In this representation, the student conducts work or research without specific guidelines established by either the university or industry. While the project or activity may draw from either entity for minor assistance, the efforts are independent of a course project or program.

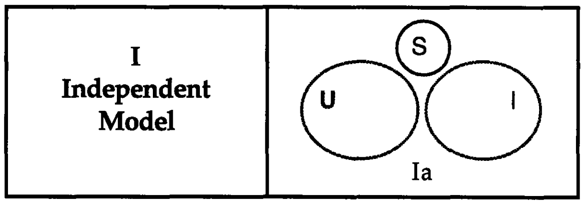

Fig. 3.8: Type **I** Independent Model of USI Interaction.

The implications of such independent work also include, however, a minimal provision of major resources and supervision. An example of an independent activity might be a student's hobby or self-initiated project not related to any course or lab, nor work position.

3.5.2 Type II: Classic and Progressive Models

These Type **II** Models, illustrated in Fig. 3.9, show two classes of interactions: Classic and Progressive. Both classes can be found in universities in varying degrees, and represent the variety of educational programs that exist that may or may not incorporate industry practice into the activities.

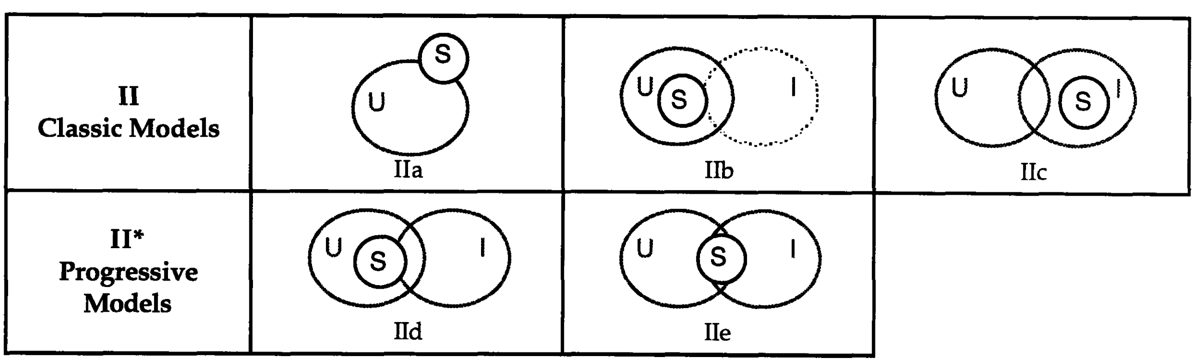

Fig. 3.9: Type **II** Models of USI Interaction. Classic **II** Models (**II**a, **II**b, and **II**c) are more commonly found in universities. Progressive **II*** Models (**II**d and **II**e) feature greater crossover from industry into the coursework.

Classic Models **IIa**, **IIb**, and **IIc** are activities traditionally employed to provide the student with hands-on experience in project work. **IIa**, for example, shows the student partially overlapping the university region, indicating an independent-study project, such as a UROP research, a supervised project not otherwise supported through an existing course, or a senior thesis. **IIb**, where the student is fully within the university region, with a dotted industry region encroaching upon the university region, would include course projects that may draw upon problems or needs of industry, but function without direct industry participation. **IIc** shows the student completely within the industry region, representing work such as a summer internship where the university plays little or no part in these activities of the student. These three types of activities are commonplace for engineering students and make up much of their professional preparation education.

Progressive Models **IId** and **IIe** are interactions that more fully integrate industry issues and practices into the learning environment. **IId** shows the industry region overlapping the university region with the student also slightly overlapping that middle region. Some undergraduate and graduate courses, such as 2.009 and 2.744, can be classified as this type of activity due to their significant recognition and issue-addressing of market needs and customer concerns. **IIe** shows the student directly amidst the university-industry overlap region. This type of interaction model would include co-ops and larger programs such as LFM, where activities are heavily dependent upon an industry sponsor, and where the student is as much a participant in the industry setting as in the university. These types of activities may form some of the capstone experiences in a future professional's education.

In both classes of Type **II** Models, however, the projects are course- or program-dependent and mostly self-contained within the course or program. Continuation of the projects outside of that context is not generally supported in these schemes due to heavy reliance on the university or industry program during the original timeline and guidelines.

3.5.3 Type III: Network Models

Type **III** Network Models shown in Fig. 3.10 are distinct from Type **II** models in one key aspect: the students are conducting their work more independently than in activities represented by Type **II** models. Hence, the diagrams are shown with the student region on the edge areas of the university and industry regions. Model **III**a shows the university and industry regions separate, indicating that the student is drawing knowledge from and responding to requirements of both institutions which otherwise have little connection (e.g. the particular companies are not sponsoring any work at MIT). Model **III**b has the university and industry regions overlapping, indicating the two institutions are somehow already involved on research or programs, and the students (and former students such as professors and practicing engineers) are also involved.

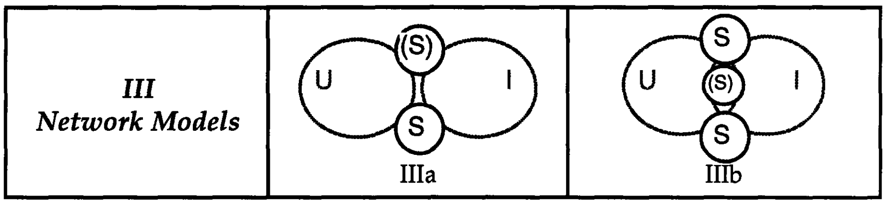

Fig. 3.10: Type **III** Network Models. **III**a and **III**b show the student working more independently, but with some cooperation with university and industry entities.

In both models, however, the key characteristic is that the student is driving the efforts or is more independently conducting the work, as opposed to being guided from within a course project, syllabus or framework. The student seeks out and contacts new sources of information, material and so on. Hence, these models are called "network models" to reflect the discovery and follow-up of new university and industry links by the students. Since the activities are based with the student, the Type **III** project can continue beyond the usual confines or limits established by the university or industry sponsor in Type **II** programs, where projects are rooted with the industry or industry program. Thus the Network Model activity is an opportunity to provide students with a transportable project beyond the constraints inherent with coursework and internships.

One implication of the Network Models is that because the student is engaging in projects at least partially detached from the protecting university or industry confines, the student is more likely to encounter issues other than those addressed in Type **II** work. These new stimuli may come from the larger community and society, providing nontraditional but equally valuable insights and influences, and encouraging possibly entirely different and creative solutions to problems. In the very least, the exposure to communications, time management, resource allocation and independent work will be valuable to the student in future endeavors.

3.5.4 Type IV: Entrepreneurial (Transitional) Models

Type **IV** Entrepreneurial Models shown in Fig. 3.11 go one step beyond Type **III** Network Models in that the students (and graduated students and colleagues) are working as a new organization, such as a potential start-up group.

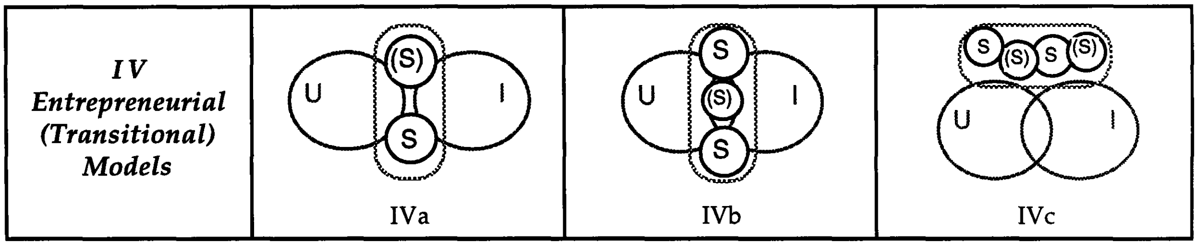

Fig. 3.11: Type **IV** Entrepreneurial (Transitional) Models. **IVa**, **IVb** and **IVc** show the students and former students working jointly as a new organization closely with both the university and industry.

These activities may or may not actually lead to the formation of a successful new company, but the project work involves those same issues and broader concerns. The Type **IV** models may also be called Transitional Models, reflecting the applicability of the lessons from Type **IV** work in school to the workplace and acknowledges the greater ease of transition the students will face once departing the university environment.

A benefit of the Entrepreneurial Models in education is that should a new venture not actually be pursued after all the research, market studies and business planning, the participants will still have the experience from conducting those studies, in addition to the experience and skills from project design and development work.

3.5.5 Type V: Work Models

Type **V** network models of Fig. 3.12 are some of the positions a graduating student may have. Model **Va** represents a faculty position, for example, while Model **Vc** shows a practicing engineer or businessperson. Models **Vb**, **Vd** and **Ve** might indicate a researcher in a joint university-industry program, a worker seeking new university-industry partnerships, and industry consultants, respectively. Model **Vf** shows a new organization, such as a start-up company, as part of industry, carrying within it the entrepreneurial (graduating) student or colleague. Other models may be diagrammed, and these five models provided are not meant to be all-inclusive.

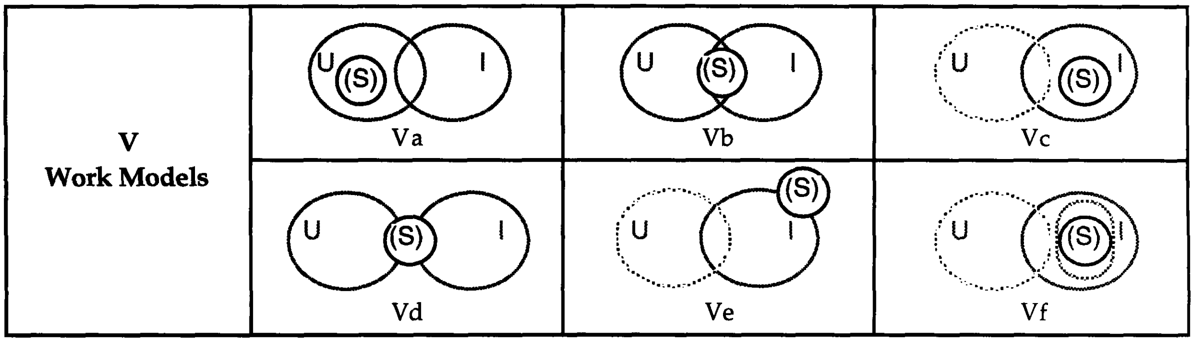

Fig. 3.12: Type V Work Models. Va through Ve show the graduated students working in or abreast the university and industry settings.

Should the entrepreneurial activities of Type **IV** projects lead to a new venture, the emerging firm becomes part of industry. In doing so, the students and colleagues of that firm are carried into the workforce via the new company as in Model **V**f as opposed to entering as individuals.

3.5.6 School-to-Work Paths

How else may these models be used? As mentioned in Chapter 2, the typical path of an engineering student may take on that as shown in Fig. 3.13:

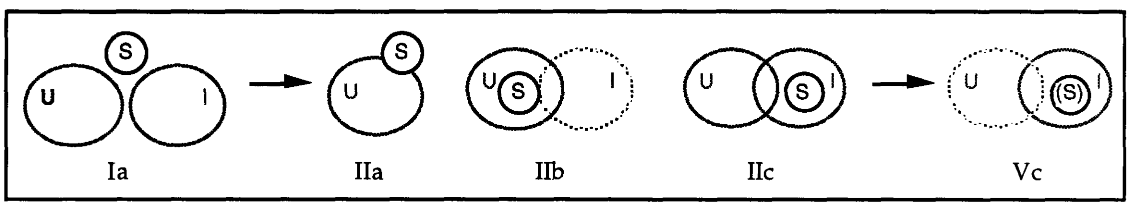

Fig. 3.13: A common school-to-work path with Classic Model education.

In this school-to-work path, the student begins with some independent work and interests (Ia), gains education through independent research (IIa), course projects (IIb) and summer internships in a company (IIc) and emerges from the university to take a position in industry (Vc). This path is a common course taken by students, and indeed is effective overall.

However, in some cases, the Classic Model educational route may not best serve those wanting different or more independent experience. Fig. 3.14 illustrates an alternative school-to-work path. It still includes a Classic Model element, such as a senior thesis (IIa) but also shows the student learning in a more student-driven Network Model activity (**IIIa**) and an Entrepreneurial Model project (**IVb**). The student then graduates and works with both the university and in industry as a sponsor and visiting lecturer (**Vb**), for example.

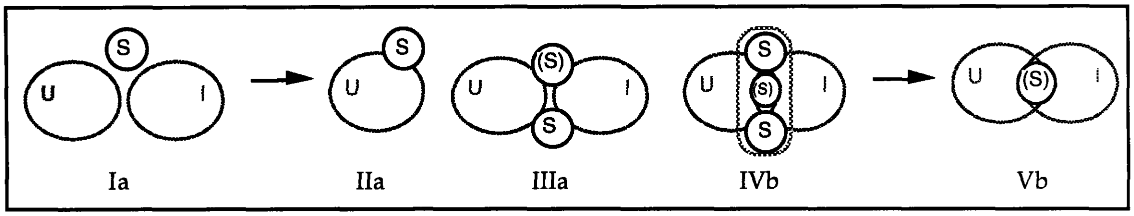

Fig. 3.14: An example of an alternative school-to-work path including Network and Entrepreneurial Model education.

Alternatively, this student may enter the workforce via a start-up, in which case the school-to-work path would end in the **Vf** model, as illustrated in Fig. 3.15.

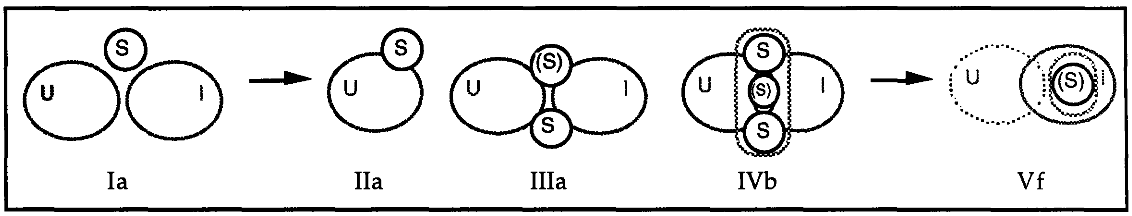

Fig. 3.15: An example of an alternative school-to-work path including Network and Entrepreneurial Model education, with the student taking a place in industry through a new start-up company.

The benefit of a university offering or supporting Type **III** and Type **IV** Model activities is that those students preferring an alternative school-to-work route (as in Fig. 3.14 or Fig. 3.15) to a common path (as in Fig. 3.13) will have the opportunity to better prepare for post-graduation roles, especially if the students pursue an entrepreneurial or innovator path (e.g. Model **Vf**).

Chapter 4

Precursors to a Product Innovation Research Program for Education

Product innovation often requires years of work, from the initial design, to patenting, to product development and marketing. Whether the project involves a simple consumer product or a more complex machine, a single project requires many different tasks conducted over a longer period of time than is typically available in a given university course. In order to design a product innovation research program for a university, an understanding of the required tasks and potential pitfalls of actual projects should be acquired.

This chapter summarizes actual product innovation efforts in the Department of Mechanical Engineering which have been closely monitored by, and in some cases worked and supervised by, this thesis author. Section 1 reviews the projects and applies the USI Interaction Models to the research activities in each case. Section 2 discusses commonalities among the projects and presents conclusions relevant towards establishing a more formal Product Innovation Research Program.

4.1 Consumer Product Project Summaries

In the following sections, case-studies involving various student design efforts are summarized. Projects vary in product area, research organization, work tasks and participant contributions. These differences reflect the variety in creativity and interests among the participants as well as the openness that must be accommodated by a product innovation research program.

While an end goal of each project is to eventually produce a real commercial product, the main deliverable of each research endeavor is the education in design, development and marketing. These case-studies serve as precursors or prototypes of the proposed program, as they were conducted in ways that would be further enhanced by the establishment of a more formal product innovation research program.

4.1.1 Lightning Archery™

Background and Project Summary

David Kronengold (SM '96) was an nationally-ranked Olympic-level archer before matriculating to MIT in 1992. Throughout his undergraduate experience, he maintained interest and passion in archery, and entered into Mechanical Engineering with hopes of applying engineering and technology to his archery activities. Even during these years, David served as an independent consultant and certified shooter in the sport, calling his service Lightning Archery™. In addition to shooting in regional tournaments, David also taught in the sport during summers. Fig. 4.1 shows David in an informal practice using a recurve, Olympic-style bow.

In the spring semester of 1995, I approached David, then a junior, after his completion of MIT 2.70 Course and learned of his desires to continue his dedication to archery as a profession. Over the next half year, I maintained a correspondence with him until the winter of his senior year. In January 1996, David accepted my invitation to discuss applying his knowledge of engineering and abilities in the sport to product design. David joined with MIT Prof. Alex Slocum and me in an independent network research activity, as opposed to a UROP or senior thesis.

Over the course of the six months to his graduation, David conducted self-motivated research of archery equipment and accessories. Working with Prof. Slocum and myself as advisors and co-developers, David conducted market research, engineering and material studies, and patent research. Having numerous colleagues in the sport, David also had many opportunities to speak with end-users and experts. David and I designed and built a prototype sight accessory, requiring basic CAD and machining, catalyzing additional interest in applying DFM and CAD/CAM for other components.

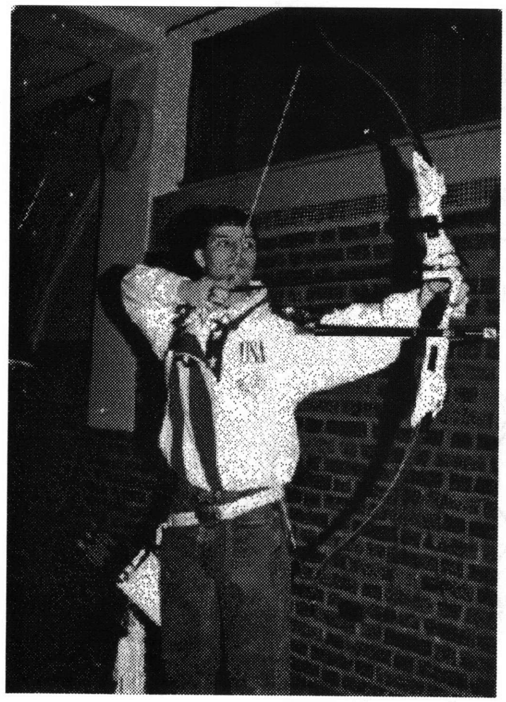

Fig. 4.1

Fig. 4.2

Fig. 4.1: David Kronengold practicing with a recurve bow.

Fig. 4.2: Prototype of the Uniflex Riser™ assembled as a compound bow. Bow image courtesy of David Kronengold, Precision Shooting Equipment, Tucson, AZ.

In the spring of 1996, David and Prof. Slocum invented the Uniflex Riser™, a new form of a bow riser which "isolates flex to the plane of the shot by decoupling the handle section from the symmetrical limb support structure."[25] In April 1996, David filed a provisional patent for the invention. He also drafted a brochure of the new design for marketing purposes. He also interviewed for jobs that semester, and, with the skills and experience boosted by these product development efforts, was hired by Precision Shooting Equipment (PSE), an archery equipment company in Tucson, Arizona.

PSE considered the Uniflex™ designs and prototyped the riser in compound bow configurations. One version is shown in Fig. 4.2. Patenting and licensing efforts are still underway at the time of this writing.

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[25] Kronengold, D. and A. Slocum. "Archery Bow Riser Design" patent application, April 1996.

Application of USI Interaction Models

Fig. 4.3 represents the design and development activities for the archery project. The figure illustrates the three stages of work, and the participants involved.

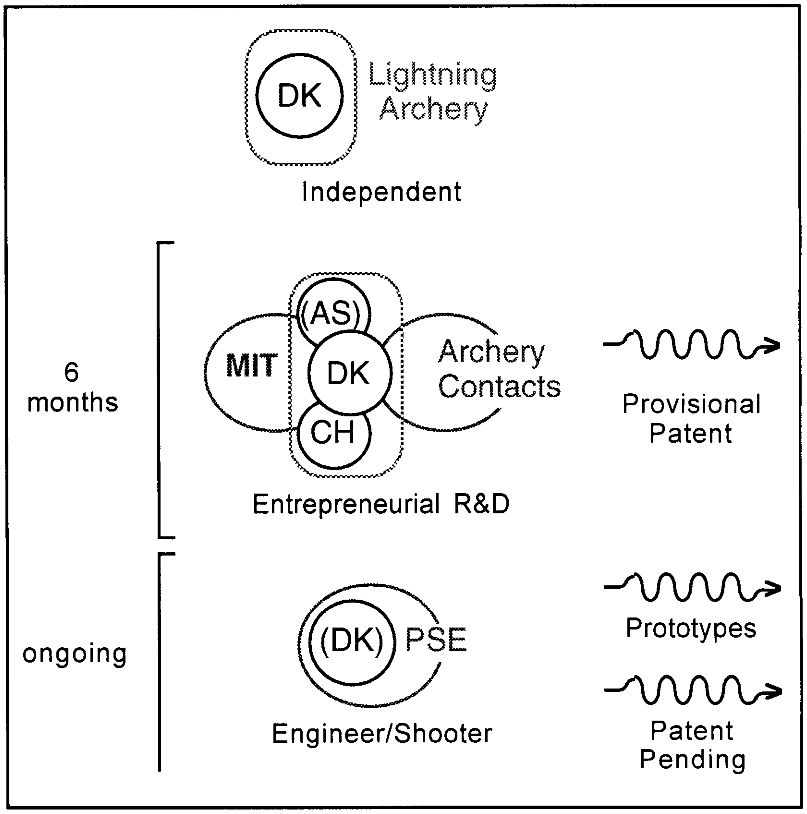


Fig. 4.3: The design and development efforts of David Kronengold and colleagues, and the corresponding follow-up by his hiring company Precision Shooting Equipment (PSE), are summarized using USI Interaction Models.

The first model shows David as an independent, as part of his Lightning Archery™ organization. The second model, that of Entrepreneurial Research and Development, shows a collective approach by David, Prof. Slocum and this thesis author, drawing information and resources from both MIT and the archery field to develop the Uniflex™ concepts. From this activity, a provisional patent was written, shown as output (a sinusoidal arrow) of the research work. While a new venture was not started, the research did consider business and licensing aspects as integral parts of the development work. The third stage shows graduate David Kronengold as a part of PSE, working as an engineer and shooter. PSE prototyped different forms of the Uniflex™ concepts, shown as output in Fig. 4.3.

This project provided David with an opportunity to practice engineering as well as business-related tasks on real product concepts: Pro/ENGINEER™ CAD and analysis model of the riser; other CAD applications for accessories; patent research and patent writing; market research; customer interaction; advertising.

David believes the application of his engineering education to his archery interests during his senior year was vital towards his confidence and preparation for work as an engineer following graduation.[26] In addition, he cites the new designs served as further evidence of his qualifications and experience during the job search.

4.1.2 Bicycle Suspension Products

Background and Project Summary

Following the 1995 2.70 Course, several students sought UROPs beginning in the summer. Under the supervision of Prof. Slocum, undergraduates Rachel Cunningham, Joe Foley, Rebecca Richkus, and Michael Schmidt-Lange undertook a design project of their choosing. After considering various product areas, they focused upon front and rear wheel retrofittable suspension systems. They followed the design process and developed novel assemblies to add vertical suspension to the bicycle wheel, as opposed to the bicycle frame. An image showing a cross-section of the rear wheel assembly rendered in Pro/ENGINEER™ is shown in Fig. 4.4.

[26] Interviews by Christopher Ho with David Kronengold, MIT, June 1996.

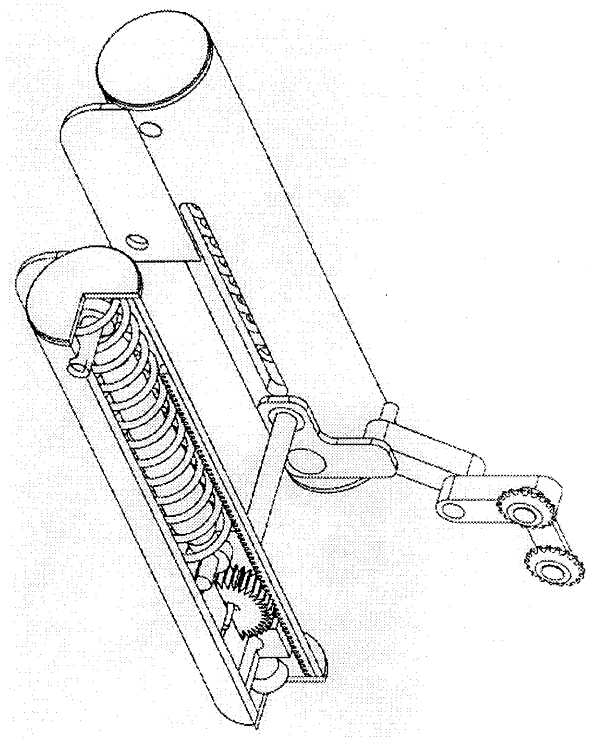


Fig. 4.4: A cutaway view of the rear wheel retrofittable suspension system, as modeled and rendered in Pro/ENGINEER.

Prof. Mohammad Durali and I also served as project managers and supervisors, as the design team continued work designing the bicycle components, both on paper, in computer models and with physical models of key mechanisms. The project continued as an independent Network R&D project after the initial UROP program ended. Students worked outside of classes and laboratory courses.

Application of USI Interaction Models

In Fig. 4.5, the first stage of the project reflects the UROP activities of the design team. With one graduate student and two professors acting as mentors and supervisors, the design team contacted various sources of information and advice regarding bicycle products. They conducted informal surveys and reviewed existing products as well as concepts described in existing patents.

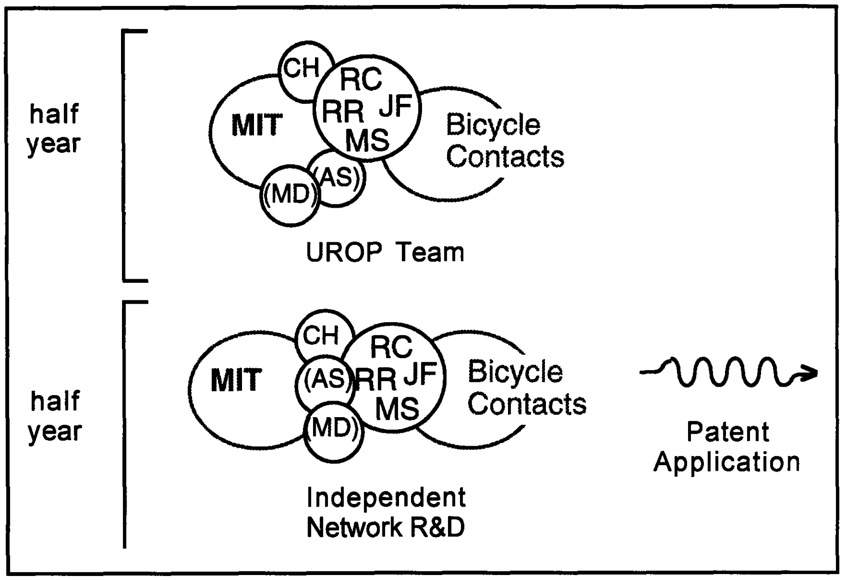


Fig. 4.5: USI Interaction Models for the bicycle suspension project showing innovation efforts moving from a UROP program to a more independent Network Model.

Following that initial UROP period, the group progressed beyond the UROP program and independently continued research and development of the bicycle suspension systems. A patent application was also begun. Unfortunately, the project is currently dormant, partially due to the departure of Prof. Durali from MIT, as well as curriculum burdens on the design team members, some of whom are graduating seniors.

Nonetheless, the year of research in innovation has provided project work experience that complements course projects (such as 2.009) and thesis, and introduced the members to the rigors of graduate studies as well as company product design.

4.1.3 Rack Animals™ and Other Lively Products

Marc Graham was an undergraduate student at MIT in design as part of his undergraduate curriculum in Mechanical Engineering. Continuing his interest in design into his Master's Degree under Prof. Slocum in 1995 through 1996, Marc developed numerous product ideas and designs, divided into the following product categories: art, music, games, and hardware.

Rack Animals™, for example, is an art-based product concept in which the ubiquitous bicycle rack can be made by metal bars bent and shaped to resemble outlines of animals.

Two sample animals are shown in Fig. 4.6. Marc designed the prototypes to be made from steel bar (e.g. concrete reinforcement bar "rebar"), and could be applied to other metal tubular material. Another art-based product are the Innovation Axiom cartoons, based upon NerdWerds™ phrases translating into more commonly stated idioms. Fig. 4.7 shows the art for one of these Axioms.

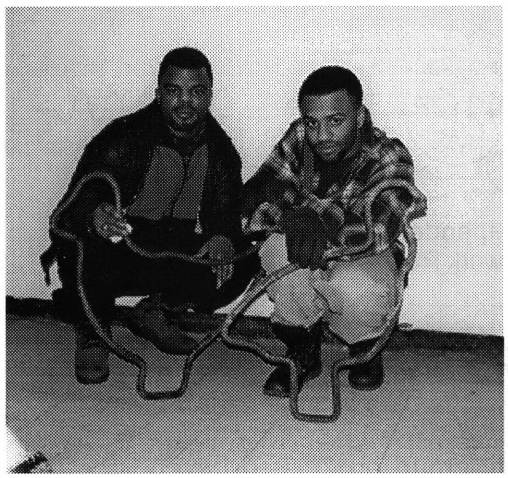


Fig. 4.6

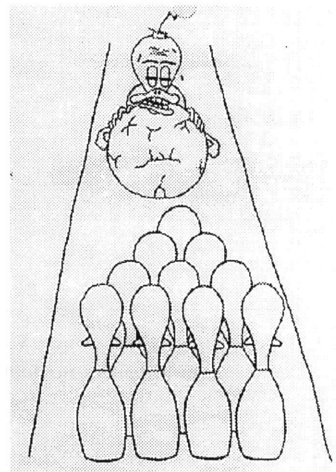


Fig. 4.7

Fig. 4.6: Marc Graham (on right) and brother Karlos display Rack Animals™ profiles to be used in bicycle racks.

Fig. 4.7: T-shirt illustration by Marc Graham for Innovation Axiom #2 "Maximize avian termination with a minimum number of projectiles." (translated as "Kill two birds with one stone.")

Marc focused on ways of making design and development accessible to students as well as others not choosing the academic educational path. With the support of Prof. Slocum, Marc looked at ways of forming a student studio and design park, in conjunction with his ideas on urban city development. Having come from an urban background environment, it was important for him to try to empower those who might otherwise be neglected by a mainstream professional community and whose creative talents may not be put to positive implementation. He wrote:

> To develop a program that is meant to improve a situation, it is first necessary to fully understand the situation.... If the creativity of the youth is not supported, it is used in a negative manner until it is eventually destroyed.[27]

Hence, Marc's activities in his S.M. program, applying design and creativity to product innovation, looked at non-traditional methods and ways of achieving invention and

[27] Graham, Marc. "Urban City Development: Program #1. Student Studio and Design Park" 1996.

development. In doing so, he addressed the issues concerning the education of his peers and counterparts in less fortunate environments.

A year after graduation, Marc is continuing work with Prof. Slocum on the Urban Design Corps (UDC), a non-profit organization focused on starting companies geared towards providing careers and resources for minorities and underprivileged people. The first product of the UDC, the Mental Block "If" musical compact disc, is discussed in a following section.

Application of the USI Interaction Models

The first stage of the design and development work in product innovation, as represented in Fig. 4.8, was Marc's graduate work with Prof. Slocum. The research involved design, development and marketing of Marc's product concepts, as well as looking for opportunities to solve problems in the urban setting. As a result, Marc produced patent applications and new product concepts, shown in the figure as output. This work continues, with Marc and Prof. Slocum contacting industry for sponsorships and support for programs such as the UDC.

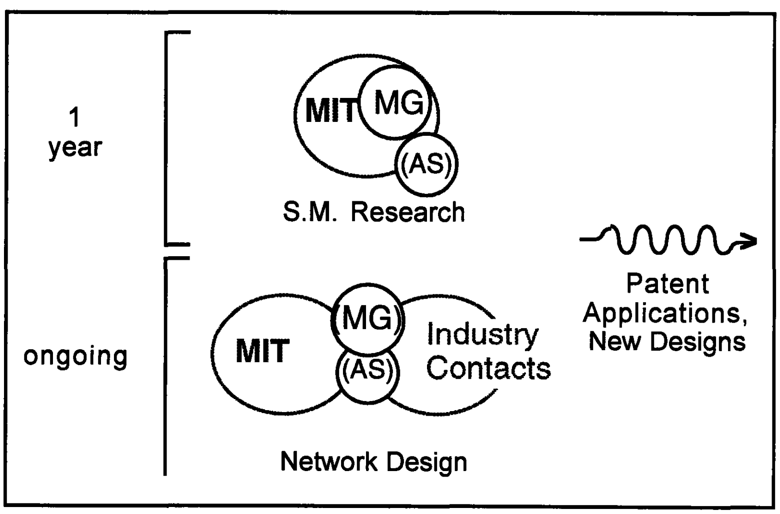


Fig. 4.8: USI Interaction Model representation of the design and development work for Rack Animals™ and other lively products by Marc Graham with the advice of Prof. Alex Slocum.

4.1.4 Mental Block "If" Album

Background and Product Summary

During the latter half of Marc's graduate program, he set out to produce a rap album performed by Mental Block, a rap group with his friends started ten years ago. However, realizing an album consists of more than just recorded sound, a cooperative effort formed, with Prof. Slocum and Aesop, Inc. as sponsors, and with myself as the graphic designer and project coordinator. As the first product of the UDC became available in March 1997, the limited-production compact disc is meant to demonstrate the feasibility of product innovation as the catalyst of urban environment empowerment. The CD, lyric booklet and inlay card are shown in Fig. 4.9.

Fig. 4.9: The lyric book (bottom), the CD and inlay card for the Mental Block "If" album.

The design of the compact disc case front cover also drew inspiration from the invention of another MIT associate. The Multi-Image™ CD case, an invention of MIT lecturer Dr. Steve Fantone, includes an integral diffraction grating on the front case panel which, with properly designed prints, can display multiple images just by tilting the case. For the Mental Block "If" album, the two images shown in Fig. 4.10 were merged.

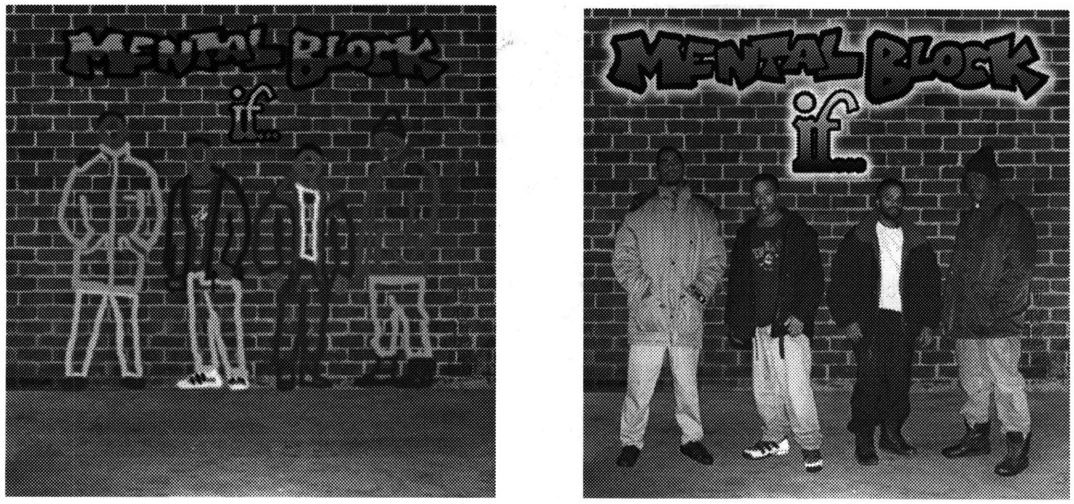


Fig. 4.10: The two images selected for the Multi-Image™ CD cover. The patented diffraction grating of the CD case allows multiple images to be seen by tilting the CD case. Images are merged through software manipulation from standard graphic files.

The CD is of particular relevance to engineering and education as it was first "released" for the 1997 National Society of Black Engineers Conference held in Boston. It continues to raise interest within MIT and in potential industry sponsors as an example of how to inspire youth to design and innovate, in subjects such as music and art.

All of the graphic design and layout was done by this thesis author. With the full support of Prof. Slocum and Aesop, Inc., a second album "Journey of the Lost Souls" is under production.

Application of USI Interaction Models

Continuing from the model representation summary of the previous section "Rack Animals and Other Lively Products," the USI Model summary of Fig. 4.11 shows a third stage of the innovation research process. Moving beyond network design, the project entered the entrepreneurial phase. With an actual product (the compact disc), the budgetary and financial issues were addressed, and cooperation with the manufacturer and printer of the compact disc components were key in the successful, on-time, on-budget production.

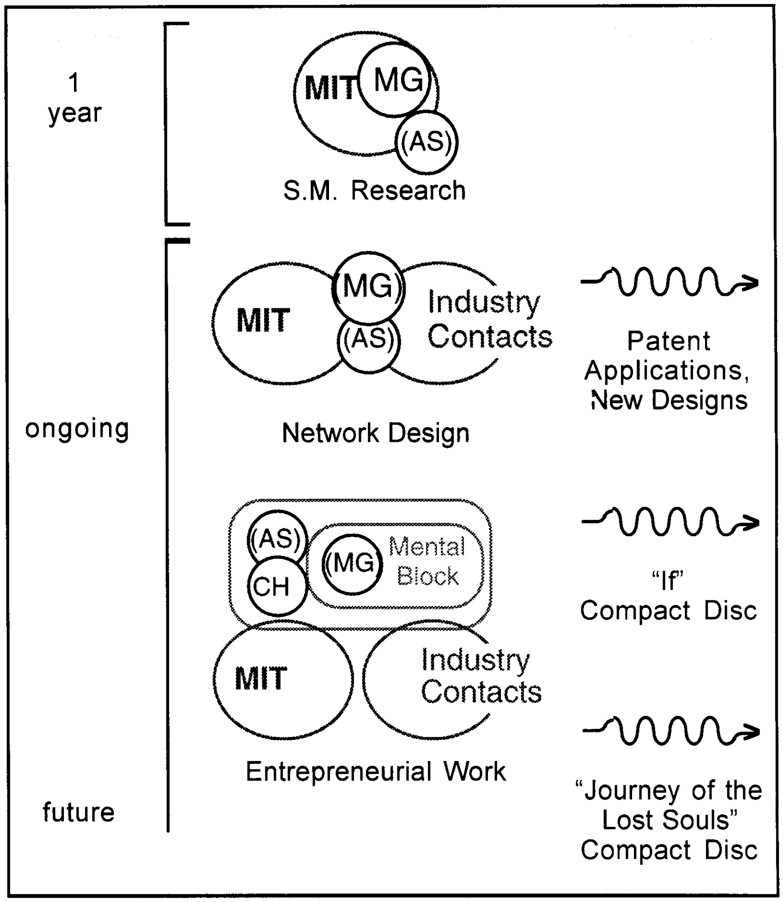


Fig. 4.11: USI Interaction Model representation of the design and development work for the Mental Block "If" compact disc and an upcoming release.

The Mental Block "If" CD project also demonstrates how a project team can function without being co-located. The musical artists reside in Ohio and North Carolina; the graphic designer conducted his work in California; the album sponsor was in New Hampshire and Massachusetts; the contract CD producer is in Maine. This shows that the overlap depicted in the USI Interaction Models need not be physical; communication, management and teamwork skills overcame the limitations imposed by geographical separation.

The connections between the entrepreneurial work of this project with MIT and industry is expected to grow. It is hoped that other corporate sponsors will take notice of these UDC efforts and contribute to the design and innovation activities.

4.1.5 TetraSponge™

Background and Product Summary

During the Independent Activities Program (IAP) at MIT, Prof. Slocum and the Office of Minority Education (OME) hold a Second Summer Program (SSP) as a 2.971 Course. For the last few years, the topic has been product invention. First-year students, many not majoring in mechanical engineering, form teams and within the one month period come up with new product ideas, introducing them with mockups or prototypes and a product brochure to a visiting group of industry representatives. In the 1997 OME SSP 2.971, a group consisting of undergraduates Melina Agosto, Teodoro Arvizo III, Sean Bradshaw, Scott Hiroshige, Nicole Thomas, and Eric Wade, invented TetraSponge™, a tetrahedral sponge with a different scrubbing surface on each side. A prototype sponge is shown in Fig. 4.12.

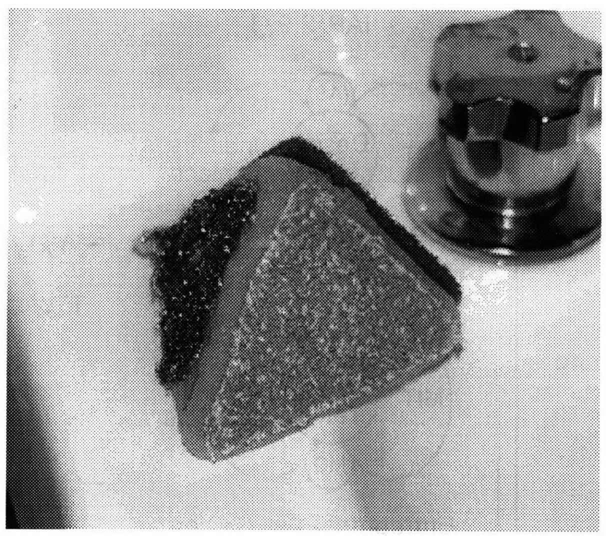


Fig. 4.12: A prototype of TetraSponge™, a multisurface sponge that provides users with four different cleaning and scrubbing surfaces on a single sponge.

Following the conclusion of IAP, however, the group continued to meet, under the direction of graduate student Martin Culpepper and Prof. Slocum. Weekly meetings are held to report progress on patent development and marketing strategies. Given leads from the final presentation contacts with industry representatives and by forging new contacts with other companies, this group is further developing the TetraSponge™ for possible commercialization.

The product innovation atmosphere is free-flowing, but with guidance provided by the two advisors. Martin serves as the primary advisor on scheduling, delegation and design issues; Prof. Slocum serves as the advisor for additional patenting advice and design, as well as contacting potential industry sponsors. The student design team does the design and engineering, as well as the market research and customer interaction.

Application of USI Interaction Models

The transformation of an IAP activity to networked and entrepreneurial efforts is summarized in Fig. 4.13.

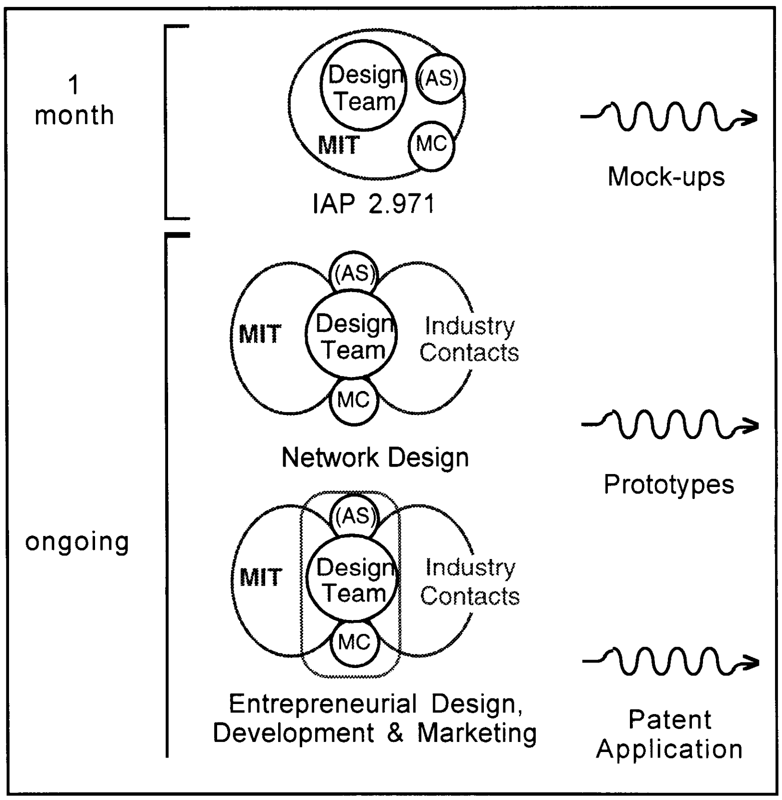


Fig. 4.13: USI Interaction Model representation for the TetraSponge™ project.

The first stage shows the design team functioning within the MIT educational setting, with Prof. Slocum and Martin advising, with a convincing mock-up or simple prototype resulting as output. The ongoing efforts are shown in the second and third stages, where additional prototypes are being fabricated by the design team. Patent work and more detailed business considerations are being pursued in the third stage (Entrepreneurial), following favorable feedback of the studies of the second stage.

Since the members of the design teams, in this project and similar ones from the IAP OME course, are first-year students, there is greater opportunity for them to progress with the innovation efforts as long as the members are committed and have adequate guidance. What is key here is the continuity and longer-term support by supervisors and the commitment by the students themselves. Whether the students stay within the department for their choice of majors, or if they choose another field, they may still continue developing the project, and can apply their experiences from outside to the tasks, and apply their education from this project to other efforts.

4.1.6 Leaf Slayer™

Background and Project Summary

In September 1995, Martin Culpepper began a Master's Degree with Prof. Slocum. Martin's project involved the design, fabrication and assembly of an improved lawn debris vacuum and sweeper. Main issues included lower cost per machine, more efficient use of power, and more effective debris collection. Over the course of one and a half years, Martin worked as the principal investigator on the project, with Prof. Slocum as thesis advisor, benchmarking current models of lawn vacuums and sweepers. The research work involved extensive fabrication and parts acquisition. It also resulted in the filing of a patent based upon the mechanisms of the device named Leaf Slayer™.

Fig. 4.14a shows Martin with some of the components of the lawn debris cleaner ready for assembly. Fig. 4.14b shows the working prototype in use on a trial lawn. Details of the lawn debris vacuum and sweeper can be found in the MIT S.M. thesis "Design of a Debris Cleaner Using a Compound Auger and Vacuum Pick Up" by Martin L. Culpepper, February 1997.

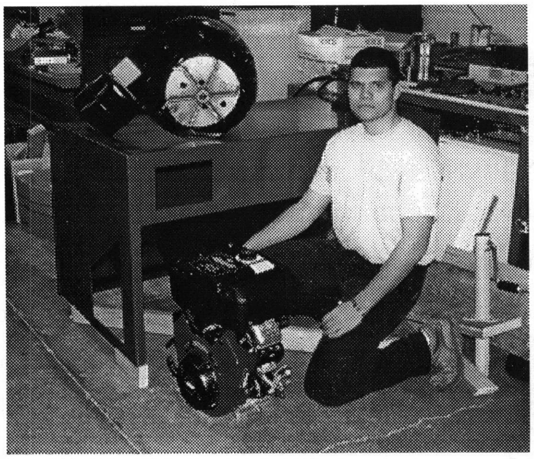


Fig. 4.14a

Fig. 4.14b

Fig. 4.14a: Designer and builder Martin Culpepper with debris cleaner components. Fig. 4.14b: The working Leaf Slayer™ prototype in use in a field in Bow, NH.

Application of USI Interaction Models

Fig. 4.15 illustrates the progress of the Leaf Slayer™ project and its ongoing efforts.

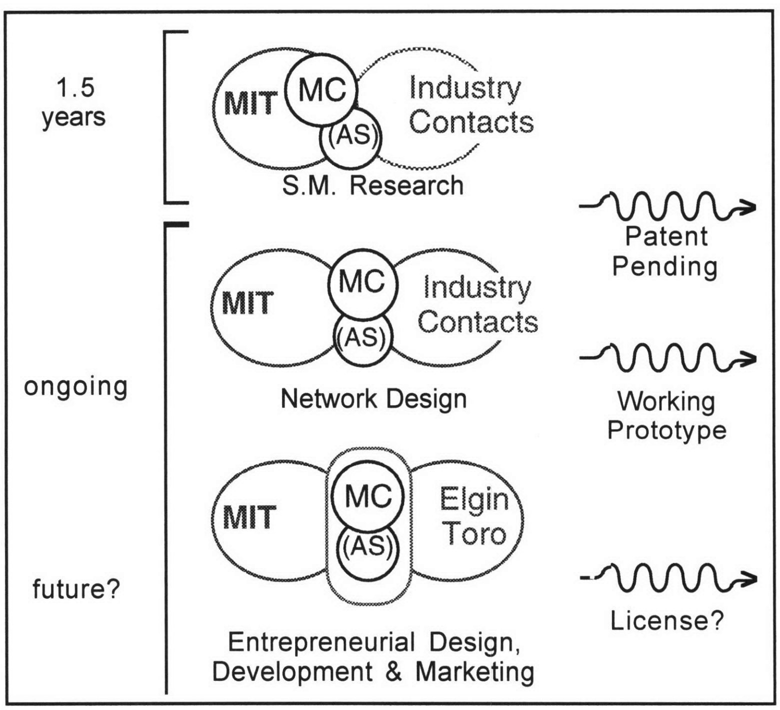


Fig. 4.15: USI Interaction Model representation for the Leaf Slayer™ lawn debris sweeper project.

The first phase shows the graduate program in which Martin worked within the MIT setting with some inquiry into existing products and technologies. The second phase, Network Design, featured Martin taking a more proactive role in industry research, and further developing the patent-pending concepts and finishing the alpha-prototype. The transition to a third stage of a more entrepreneurial outlook is shown as future work, with potential licensing and additional correspondence with companies such as Elgin and Toro.

4.1.7 StoneMasters™

The StoneMasters™ project began around 1994 when the OMAX numerically-controlled abrasive waterjet-cutter became available for experimentation in the Building 35 machine shop at MIT. The hardware for this machine was designed by Prof. Slocum, and the lab gained use of this fully-functioning prototype. After initial set-up and troubleshooting by graduate student Luis Muller, a UROP team including undergraduates Joe Foley and Isela Villanueva, with this thesis author also participating, conducted experiments to determine the working conditions and settings that would result in the best performance of the machine.

Some of the early work involved using the software layout and cutting program and determining best practices for fixtures and work setup. Experience was gained in using and complementing the computer software with other techniques and software from other applications. Later, independent work by Isela and this thesis author improved the process of converting offsite CAD designs to easily executable layout on the waterjet machine. In particular, geometric and artistic designs were selected to demonstrate the different applications that could be accomplished by a manufacturing tool.

Fig. 4.16a shows Isela with a complex cut-out in plastic that was converted from a monocolor image to the required .dxf format for the machine code. The machine cuts through metals, plastic, wood, glass and stone, including granite and other non-conducting materials, with a jet of 0.033 inch in diameter at 40,000 psi. As the machine is computer-controlled, delicate curves may also be cut, as exemplified by the rose profile cut from a slate slab in Fig. 4.16b. These designs were some of the first at MIT to introduce traditional cultural designs into the waterjet efforts.

Fig. 4.16a

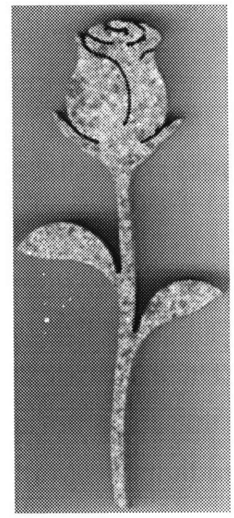


Fig. 4.16b

Fig. 4.16a: Isela Villanueva with a single-piece plastic cutout depicting a panda with bamboo. The dark curved-edge slab on the table is a table top cut from granite. Fig. 4.16b: A single piece rose pattern cut from slate using the waterjet-cutting technique.

This artistic use, and machining of small souvenirs and gifts for department functions and industry visitors led to the search for a greater market. In 1996, two groups connected with Prof. Slocum's research group considered further the abrasive-jet cutting process as a potential niche market tool. The first group, consisting of graduate students Samir Nayfeh and Ghassan Al-Kibsi, and Mohamed Khemira (MIT Ph.D. '95), began designing and making intricate stone artwork typical to the styles of Middle Eastern art. Two of these designs are shown in Fig. 4.17, demonstrating the unique capability of the abrasive-jet technology to produce designs not possible or practical with other techniques. By franchising the technology and process domestically and abroad, they hope to capture a market in the Middle East for such stonework. The repeatability, consistency and custom qualities of the process allows cultural designs to be represented in natural stone materials at quality levels not previously realized.

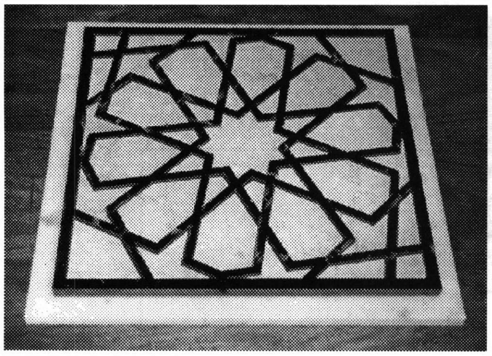


Fig. 4.17a

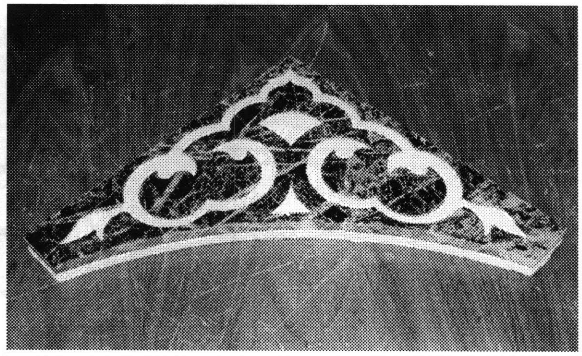


Fig. 4.17b

Fig. 4.17a: A mosaic pattern typical of those used in Middle Eastern artwork. The dark stone is a single piece, while the lighter stone pieces are individual cutouts. Fig. 4.17b: Another example of waterjet-cut stonework.

A second group, consisting of undergraduate Zojeila Flores, graduate students Martin Culpepper and myself, with Prof. Slocum and colleague Dave Gessel, are considering the domestic U.S. market for customized stone tiling. With cooperation from machine-maker OMAX, the team is approaching companies such as Home Depot for demonstrations and a trial period to gather market feedback from potential customers. The market aim is for homebuilders who desire custom stone cuts with domestic themes and styles. An agreement with OMAX and Prof. Slocum allows the purchase of initial next-generation machines at a cost-beneficial level in order to maximize the success of such a venture.

Application of USI Interaction Models

Fig. 4.18 outlines the StoneMasters™ development using the USI Interaction Models. The process development work is shown in the first two stages over a two year period by a UROP Team and by independent research students. Entrepreneurial planning took greater form in 1996, with business planning prompted by the 1997 $50K Competition. Although the competition entry did not win early rounds, the business planning continues for both the Middle Eastern group and the domestic group.

An extra benefit of the waterjet studies is new research topics, shown as output in Fig. 4.18. As more sample products are made, more techniques of the design-to-part process are developed, and additional features of the machining technology are desired. By working closely with the designers of the machine, these added capabilities can be studied and possibly implemented in future versions. Hence, this is an example of product innovation catalyzing more invention, design and development in the university with industry support.

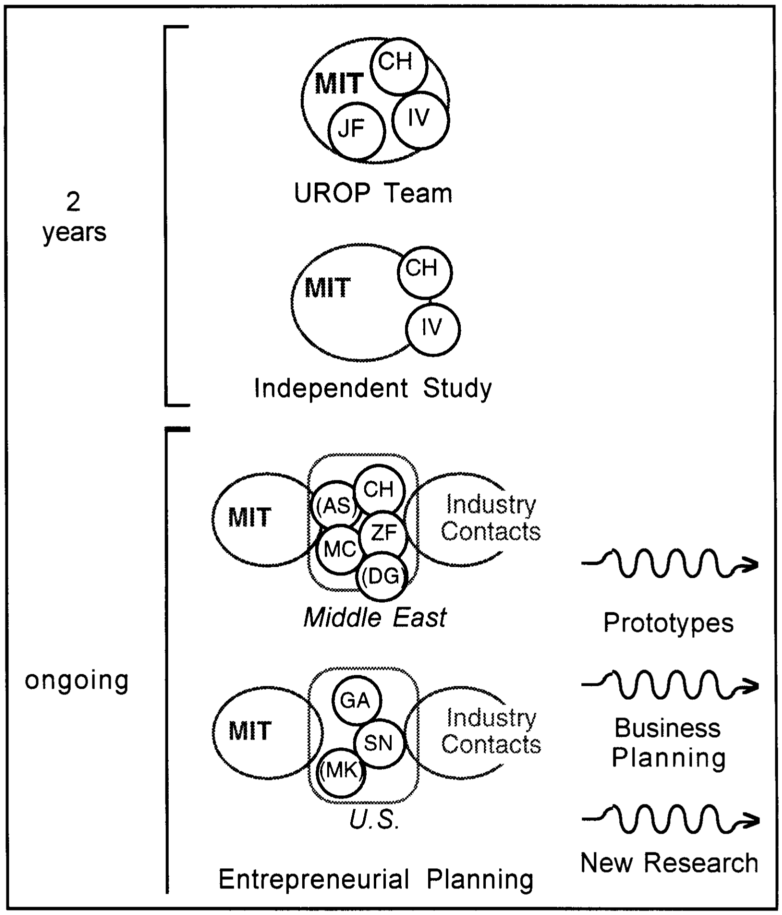


Fig. 4.18: USI Interaction Model representation for the StoneMasters™ waterjet-cutting project and goals.

4.1.8 MassagaSoap™

Background and Project Summary

Invented by Prof. Slocum, the MassagaSoap™ intermeshing soap bar changes the shape of the basic soap bar. With engineered curves and chevrons in the soap shape that do not introduce weaknesses in the bar, and protuberances designed so that two similar bars intermesh, MassagaSoap™ adds a massaging geometry that adds value, but not production costs nor manufacturing complexities. Samples of MassagaSoap™ bars are shown in Fig. 4.19.

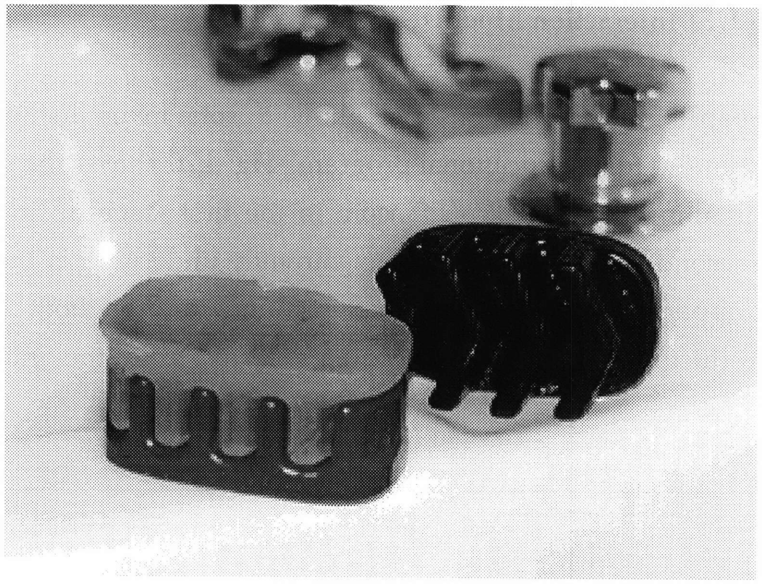


Fig. 4.19: Samples of MassagaSoap™ intermeshing soap bars.

In order to mock-up and test the shapes and sizes, as well as model and analyze specific chevron geometries, Prof. Slocum looked to the machine shop in Building 35 at MIT. In 1996, with a newly acquired hexapod machining center coming on-line, Prof. Slocum used the soap project as a way to test the machining capabilities of the hexapod and the CAD-to-part process. Graduate student Phil Houdek, a research assistant with experience in Pro/ENGINEER™ and CAD/CAM software, conducted the finite element analysis on various chevron geometries and machined with the hexapod the initial intermeshing shapes for MassagaSoap™. These machined pieces not only served as mock-ups for the soap for initial user feedback, but also as the forms used to make low-volume soap molds.

With the soap shapes and engineering analysis in hand, Prof. Slocum searched for a soap maker to produce initial volumes of soap. Buty-Wave™ Products, a manufacturer in southern California, agreed to produce an initial volume, as the soap shape innovation gives it a complementary asset with which to market its own Buty-Wave™ Soap, a soap with no alkaline or alcohol in its recipe. At the same time, domestic and international patents were filed. Similarly, graduate Marc Graham contributed lyrics and music to be used for advertising the product. A trial production of soap occurred in April, and additional runs are expected in the summer of 1997.

Application of USI Interaction Models

The MassagaSoap™ project demonstrates how a sole inventorship can contribute research opportunities to an educational program. Fig. 4.20 shows the expansion of the project from initial invention by Prof. Slocum in the first stage, to involving graduate research in the second stage. The third stage, currently underway, is the entrepreneurial and business opportunities with the manufacturer. Throughout, the outputs of prototypes, product (low-volume) and patents result from the interactions of the participants.

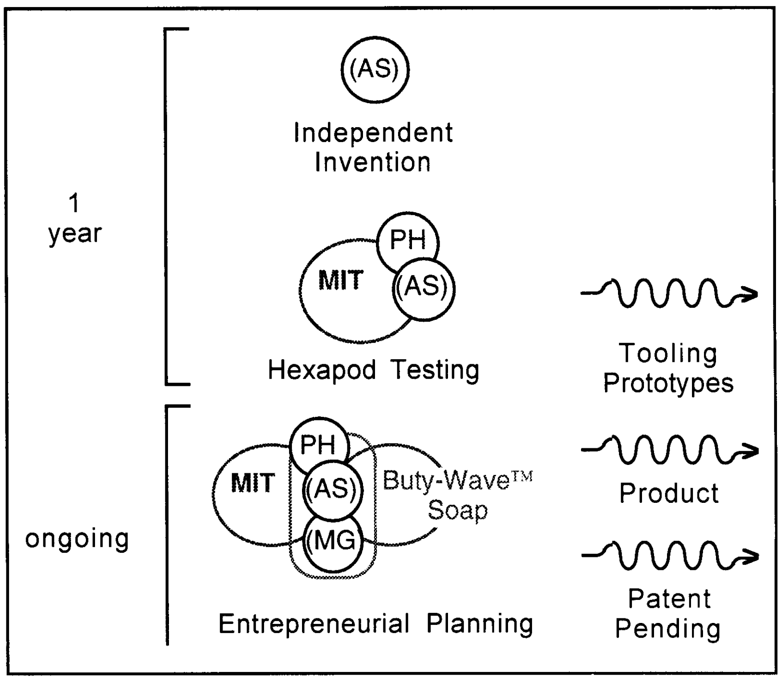


Fig. 4.20: MassagaSoap™ intermeshing soap product innovation activities represented by USI Interaction Models.

In addition, the process of bringing a product concept to market can be used to illustrate the tasks and insights of new product introductions. Financial support from the product, added credibility of MIT-related projects, as well as the inroads developed by the product marketing and correspondence, will also facilitate the design, development and marketing of the next product ideas.

4.1.9 Cubbeez™ Modular Storage System

Background and Project Brief

The search for another storage and organization system for the home, office and work area led Prof. Slocum in 1993 to spend two years devising the first embodiments of a modular storage system. In 1995, this thesis author expanded upon the original ideas of Prof. Slocum for another two years. While the project is still ongoing, with the search for market opportunities still occurring, the project demonstrates both the engineering design and non-technical complexities involved with product innovation, development and marketing.

Through the use of a fundamental new joint and novel geometrical symmetries, a structure of panels can be assembled to form an array or partial arrays of "cubbies," or spaces for storage and organization. One structure possible with the Cubbeez™ designs is shown in Fig. 4.21.

The Cubbeez™ project is the in-depth case-study of this thesis and will be discussed in detail in the next chapter.

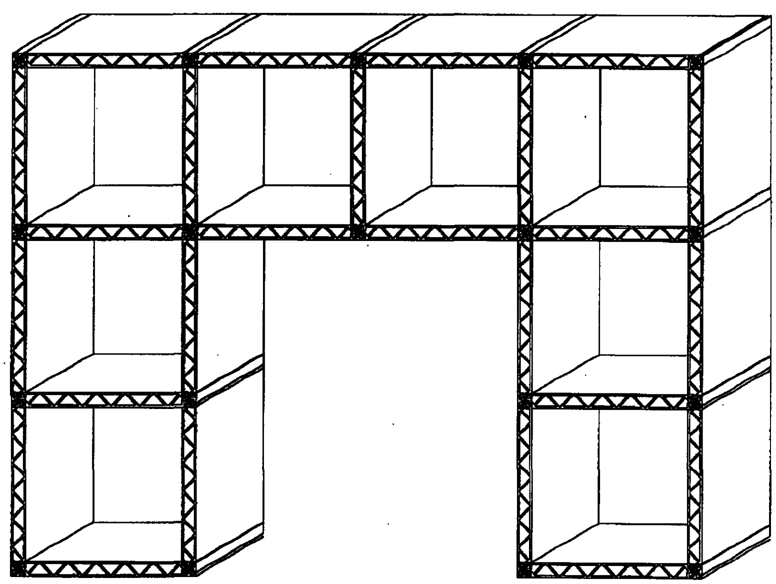


Fig. 4.21: An oblique drawing of a bridge configuration possible with the Cubbeez™ modular system components.

Application of USI Interaction Models

Fig. 4.22 shows the long-term development time already used for the Cubbeez™ project. Like the previous project case, an individual invention grew to include resource exchange with the university and industry.

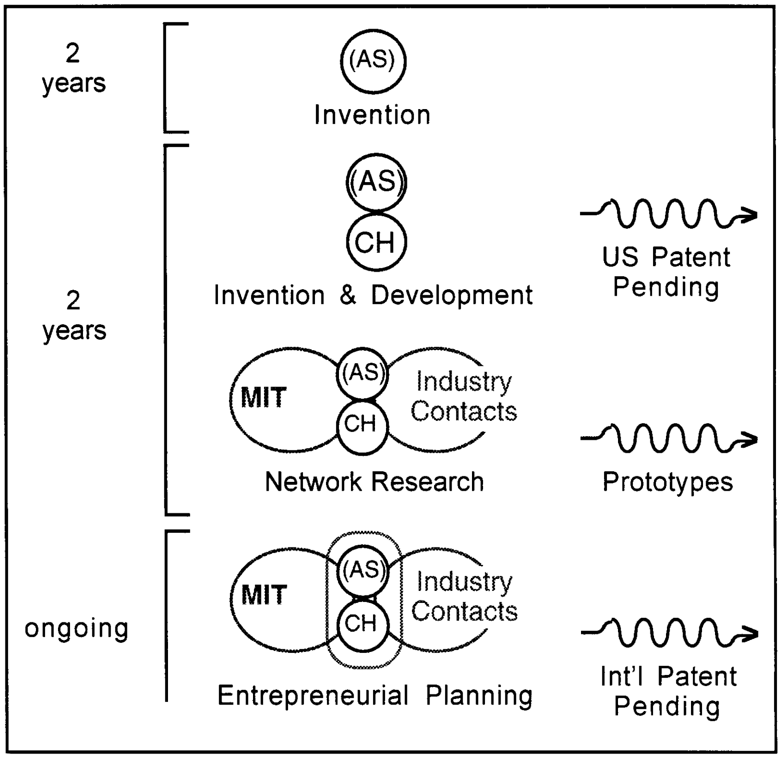


Fig. 4.22: USI Interaction Models illustrate the long-term design, development and planning of the Cubbeez™ project.

Of all the projects discussed in this chapter, the Cubbeez™ project is by far the longest running, with origins over four years ago. It has also been not only research-intensive, but required extensive market research and correspondence. Continuing efforts still depend on the integration of technical and engineering expertise with business planning and market outreach.

4.2 Conclusions for Product Innovation Research

The research and discovery exhibited in these projects feature numerous characteristics that collectively are different from other project-based educational activities. Product innovation as conducted in these projects was supported through the following:

- Extended timeline
- Shift in advisory roles
- Freedom from traditional work molds
- Empowerment of individuals with personal ownership

In addition, with added freedoms as well as added responsibility of the student, a *market pull for education* exists in the projects.

4.2.1 Extended Timeline

As the projects continue beyond the initial designs, mockups and prototyping, the required amount of time to develop the innovations is longer than one semester, the typical length of a design project in a university education. In fact, with some projects entering a second year or more, the activities are more like graduate programs in that the projects require time to mature.

In addition to the time required for students to design and iterate, there is the added, variable time of working with outside participants. For example, receiving information and quotes from manufacturers, for example, is not an overnight task, and students must recognize limitations in scheduling project tasks. Ordering material can also vary, and inconsistencies in delivery can slow the design and development process considerably. An extended timeline for product innovation is not only necessary, but also provides the students with opportunities to engage in deeper developmental tasks.

4.2.2 Shift in Advisory Roles

In a few of the projects, the faculty advisor maintains a significant role in delegating tasks and schedules, in the cases of course-related projects and sponsored programs. However, as the projects progress, the students take more control, and the faculty advisor shifts roles to one of mentoring, motivating and occasional consultation.

As the graduate students involved in these projects experience their own innovation projects as designers and drivers, they gain the insights needed to manage other groups of innovators. Hence, training and managing through apprenticeship proved to be an effective way to expand product innovation practices with limited human resources.

The students now driving their projects with graduate student managers and a faculty champion may eventually be prepared to lead others in their own innovation pursuits.

4.2.3 Freedom from Traditional Work Molds

Defining the design problem itself is open for students to determine. This freedom of choice also leads to the responsibility of defining tasks and deliverables, and the delegation of resources to those activities. Cooperation between the project team members and managers is different from the often pre-established working structure of courses and lab teams, and organization from one innovation project to the next may be quite distinctive.

Reflecting risks and rewards similar to those in companies, the product innovation actions are conducted for the success of the project, not just the completion of the project. Since the project's success is not evaluated by a grade or exam, but rather the quality of the product and the students' experiences, the "return on investment" of effort by the student is determined with different issues than in typical course projects. A more personal incentive for contributing to the project motivates and catalyzes students to take action.

4.2.4 Empowerment of Innovators

Though the word "empowerment" may sometimes be considered a vague, vacuous buzzword, the product innovation projects do empower the students by shifting, as much as possible, the project definition, decision-making, resource allocation, scheduling and other responsibilities to the students on the projects. The managers, whether faculty or graduate students, assist in setting goals and tasks, but the energy and contributions are nonetheless supplied by the student team members. Empowerment and educational enrichment result from the students gaining the confidence and wisdom of developing innovations and taking the initiative, and the new skills enable them to apply themselves to other challenges.

4.2.5 A Market Pull for Education

The typical approach of education is "market push" — an educational institution pushes education onto students through homework, assignments, projects and exams, confined to within the course or lab environment. While course projects may require that the students go outside of the academic setting to complete the work, the student demand for education is often passive while the university supply of work is active.

However, in the product innovation activities, the situation is a "market pull" for education. Students wanting to develop innovations and designs seek out information, tools and skills, and find ways of satisfying those demands. The return of information as a result of that demand is wanted and directly applicable to the project, unlike coursework having no immediate application for the student. The market pull also creates a proactive learning system in which students learn how broad or deep they must delve into a subject to produce meaningful results.

Chapter 5

Case-Study: Modular Storage Systems

This product innovation project is an example of concurrent design and of *concurrent development*. That is, at every level of design (from conceptual, embodiment to detailed design) and in development and marketing phases, critical areas and tasks in engineering and in non-technical fields were simultaneously addressed. In the initial development stages, the designs were heavily influenced by, but not limited to market research, patent research, technological feasibility studies, and the voice of the customer. Similarly, detailed designs were heavily influenced by company cost goals, existing and complementary products, and the current state of manufacturing processes available, for example.

To reflect the complex nature of this design and development process, the project is described in a roughly chronological order in Section 1. Engineering and design details are presented in Section 2, which includes finite element analysis results and an explanation of design attribute selection and calculations. Section 2 also includes discussion on: manufacturing and material issues, process limitations, cost and pricing, and the effects on design. Management analysis tools specially modified for application to innovation and entrepreneurism are described in Section 3.

A subset of inventions and associated systems are discussed in this chapter. For details of all inventions and designs of this case-study, refer to Appendix B, the patent application from which the focus of this project originates.

5.1 Development of the Innovation

The project started with the identification of a need, incorporated market issues and technological factors, and continues with additional research and development. Designs went from mere diagrams to detailed engineering drawings; from rough mock-ups and simple profile cut-outs to prototype extrusions for proof-of-concept; from one set of applications to a wide range of potential uses; from single inventors to a network of firms working for multiple goals. Table T5.1 presents a broad-view timeline of the project. Note that the project is ongoing, as company correspondence continues.

~1993	Prof. Alexander Slocum addresses storage problem. Objects in home and office need to be organized. Develops initial designs.
Sept. 1995	Christopher Ho expands on ideas, resulting in numerous new concepts.
Oct. – Nov. 1995	Waterjet-cut samples made. Companies contacted for manufacturing assistance, reference and potential licensing of product designs.
Dec. 1995	Patent application completed in common prose; sent to Rines & Rines for "legalese-ization." Search for industry partners continues.
Feb. 1996	U.S. Patent filed. More design and analysis conducted.
March – Aug. 1996	Market search continues. Axisymmetric barb joint further improved.
Sept. 1996	Charmilles Technologies completes EDM dies. Barbour Plastics extrudes first clips.
Nov. 1996	Barbour extrudes second set of clips; Clippeez™ tested with polycarbonate panels and medium-density fiberboard. First contact with Rubbermaid; VP of R&D responds to Cubbeez™ brochure.
Dec. 1996 – Jan. 1997	Rubbermaid negotiations continue. Rubbermaid delegates marketing and engineering staff to the project.
Feb. 1997	Patent Cooperation Treaty filed for international patenting. Trexel introduced to Cubbeez™ project for microcellular plastics research.
March 1997 – Present	Rubbermaid conducting in-depth market and engineering studies. Ho & Slocum continue market survey and manufacturing research.

Table T5.1: Timeline of modular storage system project. Initial design began in 1993, and research and development continues into and beyond the fourth year (1997).

Although the Cubbeez™ project has not concluded, many steps in the design, development and marketing processes have been addressed, and several obstacles have been overcome. This section summarizes the project tasks and key issues.

5.1.1 The Need for Storage Solutions

At home, at work, in stores, in schools, there exists the need for storage and organization of items and objects. Original work began when Sematech asked Prof. Slocum to design modular cubes. After making an early design, Prof. Slocum, father of three, looked about his own settings and household, he saw a sight all too familiar to people everywhere, especially to those with children: shoes, gloves, toys, household items, office supplies and the like strewn about. For others, the accumulation of things also requires the organization and storing of those things for later or frequent use.

When function and cost are considered, the need for practical and affordable storage solutions becomes even greater. With living and working space at a premium, an organization system should be robust to a user's needs without incurring additional cost burdens associated with the product. In some markets, for example, commercial services can charge between $25 and $125 per hour, in addition to the actual storage containers or systems themselves, for clients wanting outside assistance to solve their particular storage and organization needs.[28]

The storage solution must also conform to the environment of the application, the potential customer's resources, and changes in the environment and the resources. Other issues that should be addressed include:

- Effects of design on retail space, inventory, shipping volumes
- Means of transport from store to location of use
- Time from purchase to product use
- Variation of storage item properties (size, shape, weight)
- Customization and expandability
- Quality over time, wear, use, abuse and misuse

[28] Krino, G. "Busted!" The Orange County Register, Dec. 28, 1996. Accent section, pg. 1.

5.1.2 Existing and Related Products

In the home, there are countless areas which can be served by storage solutions. Figs. 5.1-5.5 show several situations. Some of the customer requirements may include:

- Low cost
- Stability and robustness
- Compartmentalization
- Non-permanent attachment to room walls or building
- Infrequent assembly or disassembly
- Collapsibility for transport and storage of storage system itself

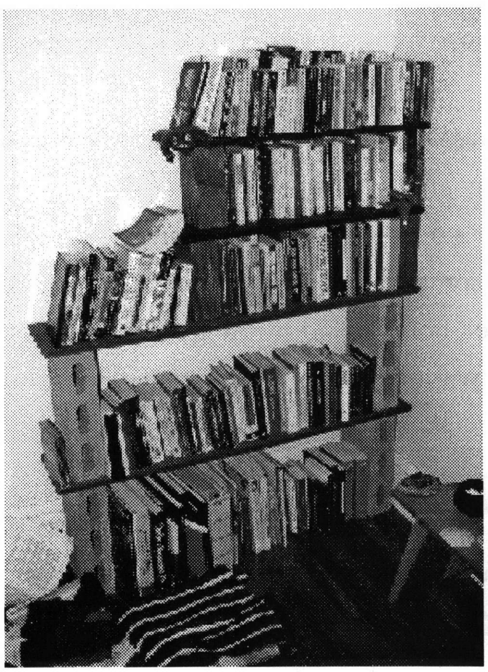


Fig. 5.1: Shelves of boards and bricks form a makeshift bookshelf.

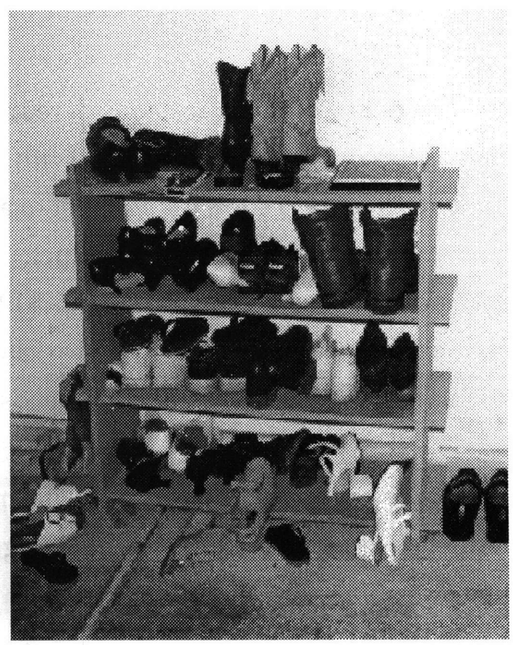


Fig. 5.2: Shoe rack made of particle board.

Fig. 5.3: Side-stacked plastic containers may be insecure and can buckle.

Fig. 5.4: Stackable shelves provide little compartmentalization.

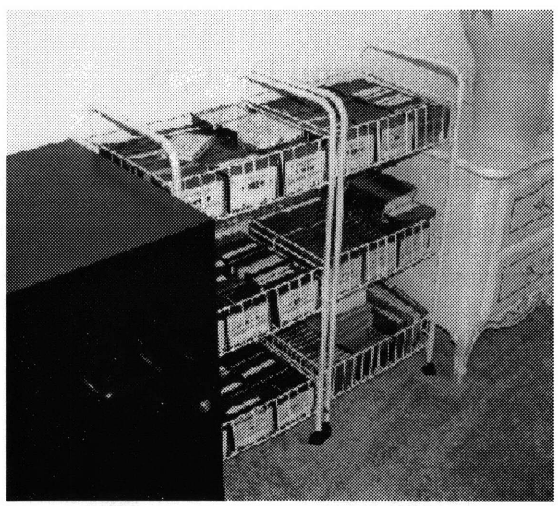


Fig. 5.5: One-piece units offer no expandability or customization for efficient use of space.

The products or storage systems depicted in Figs. 5.1-5.5 have more expensive alternatives, as well as specifically-designed storage systems for each use. For example, bookshelves and cabinets of wood or metal could easily solve the storage needs. But is there another option that satisfies the requirements such as low cost, stability, and modularity? Consider end-users such as:

- People on low incomes or low budgets
- Parents with changing needs over time (e.g. growing children)
- Those with seasonal storage applications (e.g. wintertime gloves, boots, hats)
- Elementary schools needing spaces for students' belongings
- Tenants not allowed to make structural changes to the residence
- Residents with non-standard desired storage space (e.g. college students in small dorm rooms; garage owners with floor-to-ceiling applications)
- People without the means of transporting large or heavy products (e.g. people using public transportation systems)
- People without the time, tools, building supplies or know-how for custom-made systems
- Companies needing industrial storage systems for long or atypically-shaped items
- Retailers wanting modular display and inventory structural systems

5.1.3 Summary of Inventions and Designs

This section briefly summarizes the broader concepts of the modular storage system solutions. Section 5.2 explains the concepts in greater engineering detail and provides quantitative guidelines for designing, configuring and applying the innovations to a given situation.

The Unit Cubby

In 1993, Prof. Slocum set out to solve one of the nagging problems in his home and office, as well as at colleague's companies. One of the original designs was that of a unit "cubby" (or the volume of space called the "cubby hole") that could be attached to one another to form a larger structure of those cubbies. The unit cubby, made of aluminum plate, had attached to it plastic Duplo™ plates, plates with studs and sockets that allow for mating between similar plates. Fig. 5.6 shows the prototype system of seven unit cubbies attached to one another in a bridge structure attached by these Duplo™ plates.

Fig. 5.6: Aluminum unit-cubbies connected by plastic Duplo™ plates form a bridge structure storage system. Although the system does not fully accommodate the office products, the system demonstrates the effectiveness of adding a storage system on a tabletop with unit-by-unit compartments. Designed and built by Prof. Alex Slocum in 1993.

Some of the disadvantages of this system include: long fabrication time; waste of cubby hole space due to double walls; high cost; non-collapsible unit cubby. However, the benefits of such a system include: interchangeable cubby units; expandable system; customizable structure configuration; structural rigidity and stability.

Interlocking Cubby Panels

Given those disadvantages and advantages, Prof. Slocum in 1995 devised a system that could overcome those advantages. With this thesis author in late 1995 modifying and expanding the scope of the inventions, the Cubbeez™ project (pronounced "cubbies," not "cube-ease") took on new forms. The new designs are illustrated in Fig. 5.7 and Fig. 5.8. This form of the unit cubby, represented in the oblique drawing of Fig. 5.7, consists of four panels that interlock at the corners by sliding mating features on each panel in the direction orthogonal to the open face of the cubby. With certain joint designs at the mating sides of the panels, any force in the plane of the cubby face will be resisted, and the cubby will not separate.

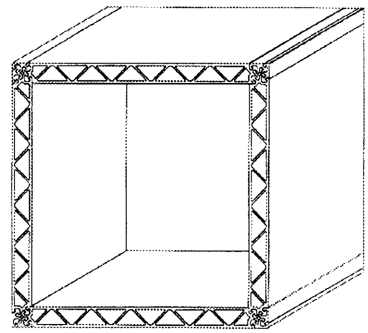


Fig. 5.7: A modular unit cubby consisting of four interlocking panels.

Increased Efficiency: The Cubby Ratio

Fig. 5.8 shows a 2x3 array of paneled cubbies, with contiguous or neighboring cubbies sharing the panel between them. This reduces part count and presumably preserves more space for the cubby storage volume instead of being wasted by redundant walls.

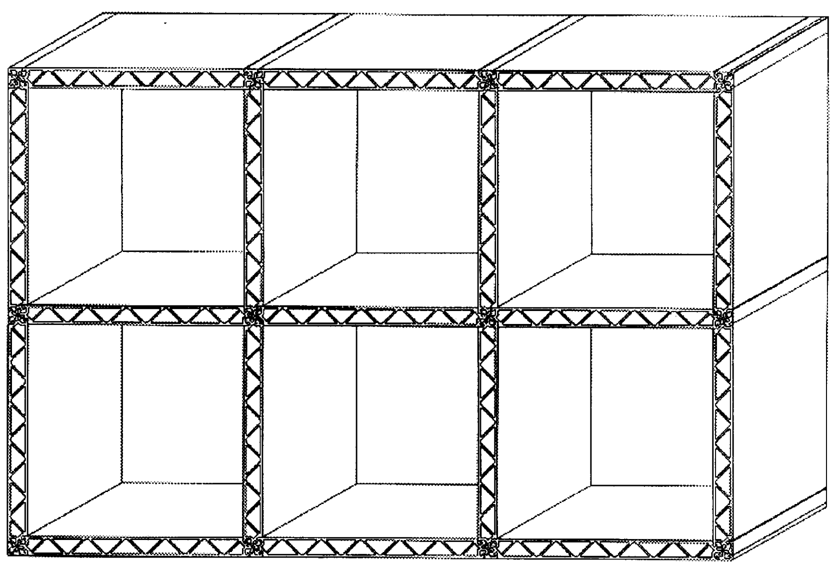


Fig. 5.8: A 2x3 array of paneled cubbies uses fewer panels (17 sides) than unit cubbies that do not disassemble (24 sides) as in Fig. 5.6.

For any regular rectangular array of m by n cubbies, the number of panels per cubby equals the "Cubby Ratio":

$$\text{Cubby Ratio} = \frac{n(m+1)+m(n+1)}{nm} \qquad \text{(E5.1)}$$

Thus, for a single cubby, with $m=n=1$, the Cubby Ratio equals 4. This is the most inefficient use of the panels, with four panels in use for only one cubby hole. For the 2x3 array of Fig. 5.8, $n=2$ and $m=3$, resulting in a Cubby Ratio of approximately 2.83. As n and m increase, the Cubby Ratio in Eqn. E5.1 approaches 2. Note that this is half of the worst case of 4 for the single unit cubby.

Bridge Structures

As demonstrated by the unit cubby structure of Fig. 5.6, a bridge structure can be assembled. With wall-sharing cubby panels, as shown in Fig. 5.7 and Fig. 5.8, bridge structures may also be assembled. Fig. 5.9 shows one bridge configuration using 25 interlocking cubby panels. Note that using non-collapsible unit cubbies would require 32 walls (8 cubbies x 4 walls per cubby).

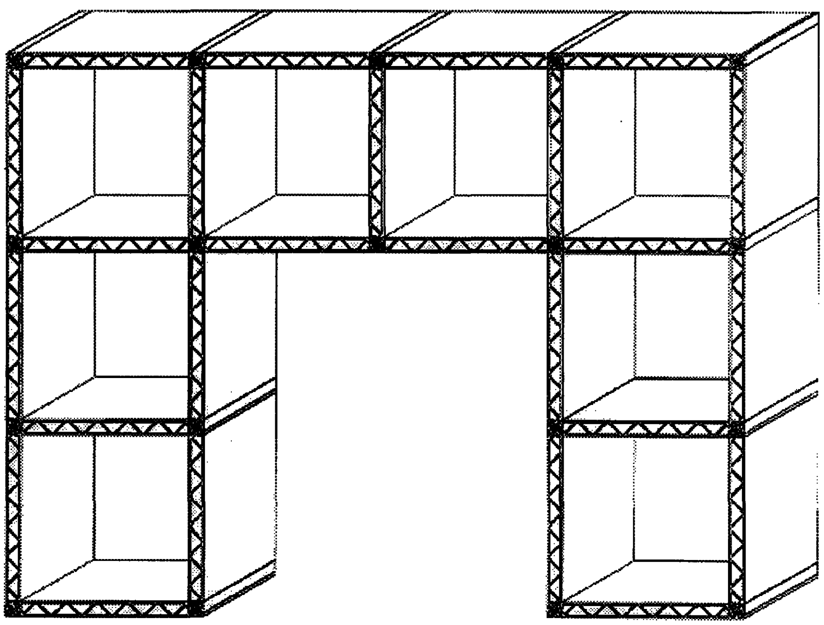


Fig. 5.9: A bridge structure can be assembled using the interlocking panels used to make wall-sharing cubbies. This particular structure uses 25 panels for 8 cubbyholes and the bridge space.

Fractional Panel Widths for Cubby Customization

As is evident from Figs. 5.1 through 5.5, it is often desirable to have cubbyhole spaces of different sizes and proportions for different object. By providing a set of *fractional panels*, cubby structures can form storage spaces not limited to squares or even rectangles. Fig. 5.10 shows a modified cubby divided into smaller areas by using quarters fractional panel widths (full, three-quarter, one-half and one-quarter sizes).

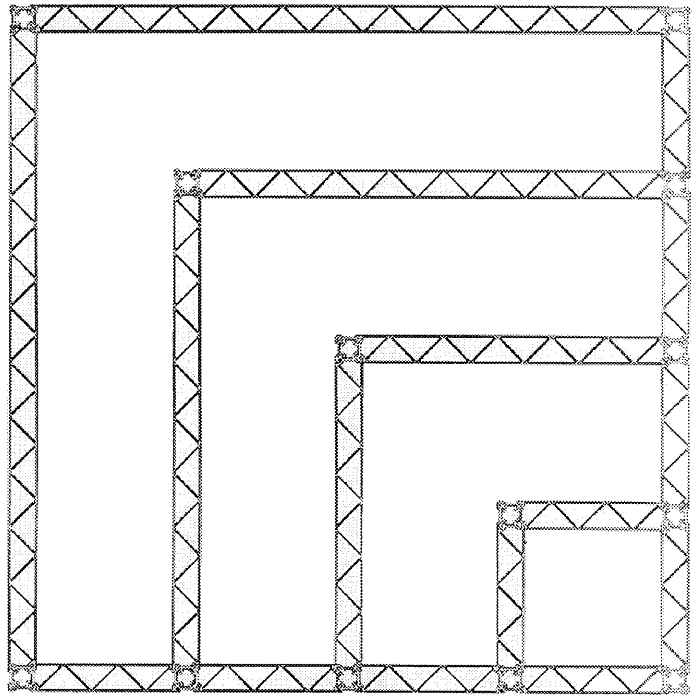


Fig. 5.10: A cubby structure comprised of fractional panels of full, three-quarter, one-half and one-quarter widths.

Other fractional schemes may be used, such as thirds fractions (full, two-thirds, one-third). As will be discussed in later sections, however, the number of fractional panels selected has significant effect on manufacturing and marketing considerations.

Angled Structures

By merely reorienting an appropriately assembled structure, angled structures can be created. For example, the cubby structure in Fig. 5.11a consists of full and half panels and is tilted at a 45° angle to the plane of the panels. Such a structure could be used a wine rack or for cylindrical objects that will settle in a cubby hole bottom corner as shown in Fig. 5.11b. As the panels interlock at the cubby corners orthogonally to the cubby face, the structure is not susceptible to unwanted disassembly.

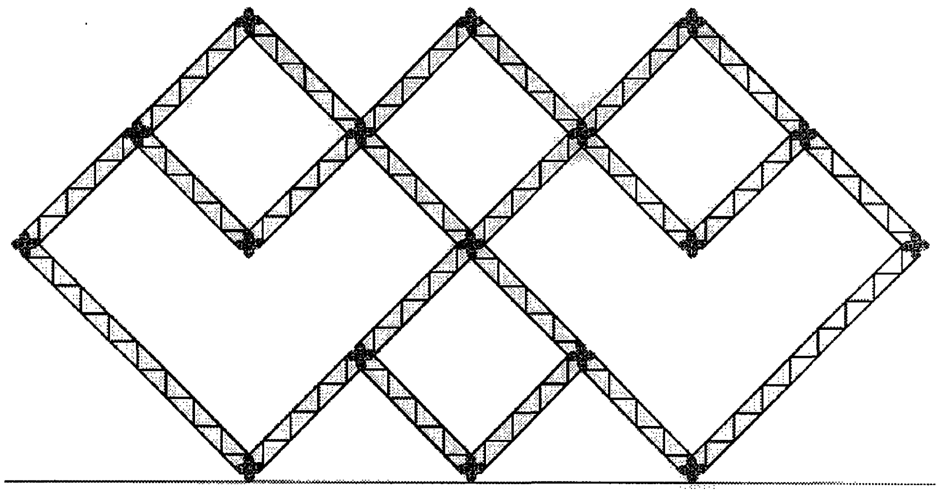


Fig. 5.11a: Angled structures may be configured with panels at off-angles, shown here at 45°, providing more possibilities for storage solutions.

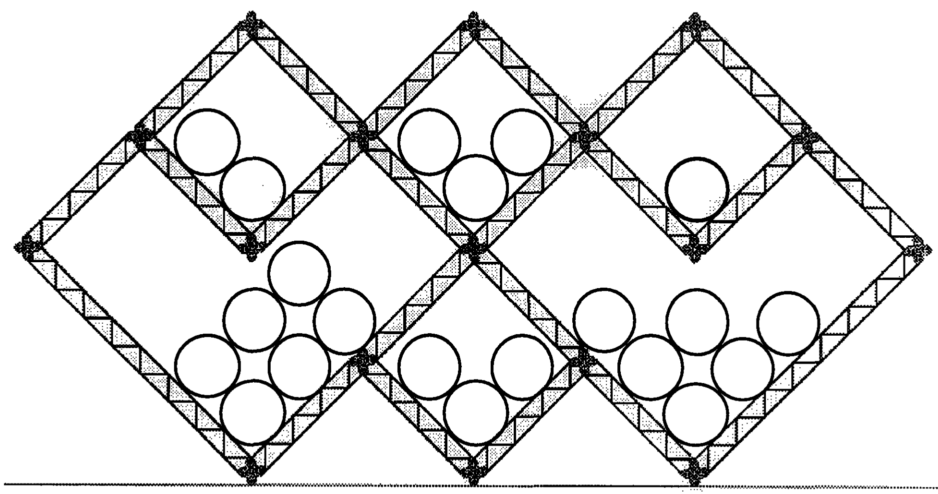


Fig. 5.11b: The angled structure depicted in Fig. 5.11a is well-suited to hold cylindrical items, such as wine bottles.

Panel Rearrangement

The interchangeability and symmetry of cubby panels allows a structure to be disassembled and then reconfigured into a different arrangement of cubby holes with a minimal number of surplus of parts or shortage of parts. Thus, if the needs of cubby system changes, the user can change the system as required with little inefficiency. Fig. 5.12 shows one embodiment of the cubby system using full, two-thirds and one-third fractional panels. Fig. 5.13 illustrates a much different arrangement, but uses the exact same number of panels.

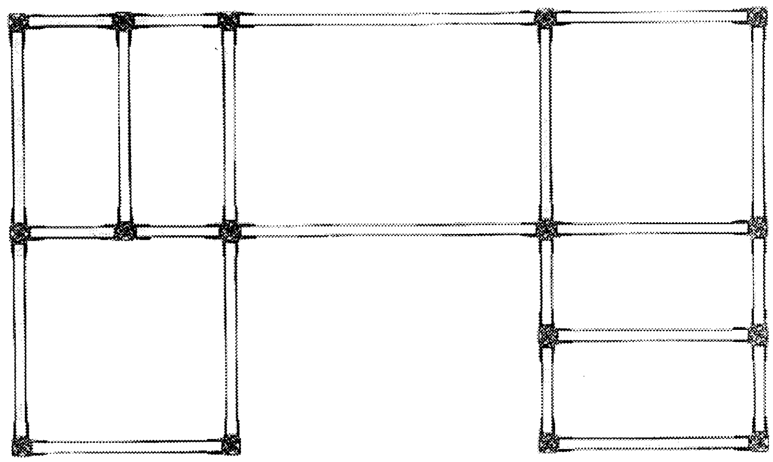


Fig. 5.12: Fractional panels are used to make this cubby system. 2 full panels, 12 two-thirds panels, and 8 one-third panels.

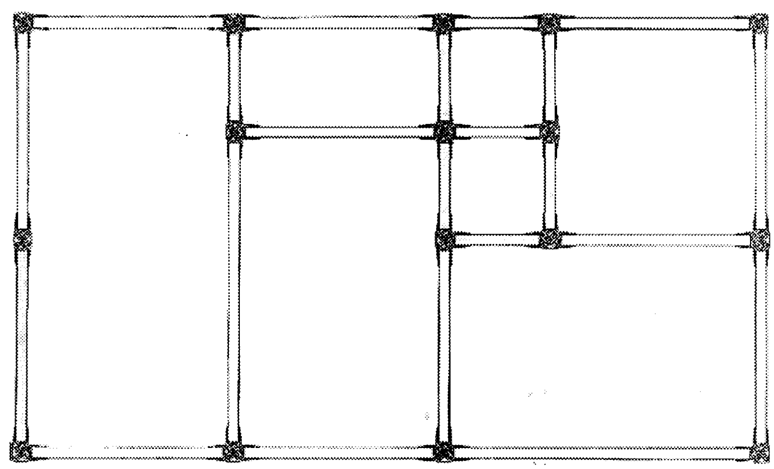


Fig. 5.13: The same number of fractional panels as in Fig. 5.12 are used to make this cubby system.

AxiBarb™: A Four-Fold Rotationally-Symmetric Barb Joint

In order to resist loads in any direction along the cubby face, and to provide the multiple symmetries that allow identical panels to be slid together, the design of the joint ends is critical. The invention involves a class of rotationally-symmetric joints, in which a male protrusion is matched by a female mate at the other side of the joint end, as illustrated in Fig. 5.14, an end view showing four barbed elements (three panels and one end-only "terminator") interlocking.

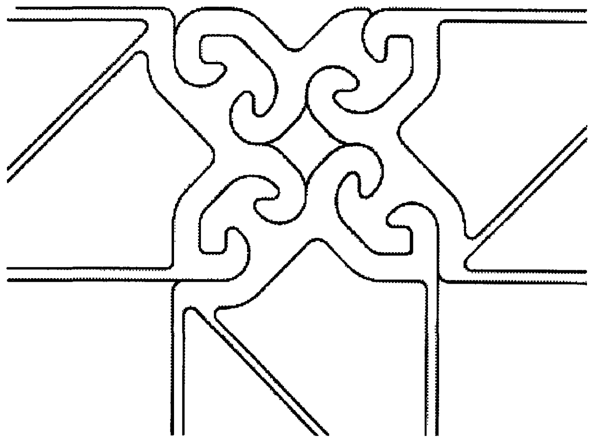


Fig. 5.14: The standard close-packed AxiBarb™ joint configuration forms an almost fully occupied joint region, with most surfaces touched by neighboring mating surface.

Rotation of the joint by 90° around the joint region center axis results in the identical joint region features. Hence, the AxiBarb™ joint exhibits four-fold rotational symmetry. Also, as discussed below, the panel elements themselves are rotationally symmetric: rotating the panel by 180° along its depthwise central axis results in the same location of the joint features. Thus, the panels exhibit rotational symmetry as well.

Variation of the AxiBarb™ Joint: Offset Joint

Depending on the loads on the joints and panels, variations of the standard barb joint may be used. The offset barb joint, shown in Fig. 5.15, has the barb (and corresponding barb-mate) offset by one nominal barb thickness to the outside of the panel. Closer inspection reveals that this decreases the amount of mated surfaces and may create small flexural regions in the joint, but the wider spread of the barb and barb-mate pairings provides wider resistance for the joint under moments.

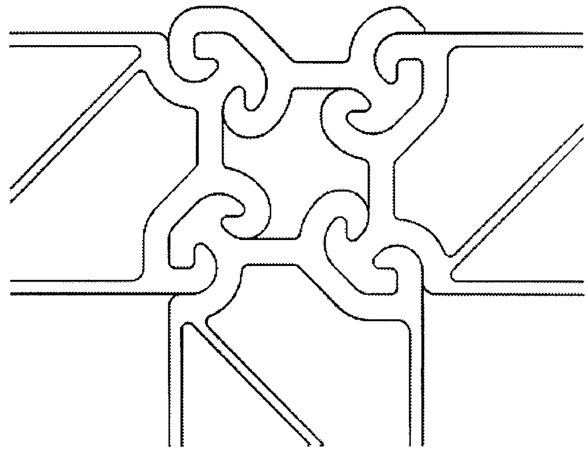


Fig. 5.15: The offset barb joint moves the barb and barb-mates outward to provide wider resistance to moments.

Another trade-off is that the terminator (the element without the panel wall component) is not flush with the surface of the panels of the neighboring joining elements. In some applications, this flushness may not be important.

Variation of the AxiBarb™ Joint: Spread Joint

When the nominal barb thickness is less than one-tenth of the joint region, as determined by the chosen overall panel thickness, then a spread barb joint is used. The barb and barb-mate features are moved outward to maximize joint moment resistance. Fig. 5.16 shows an example of a spread barb joint.

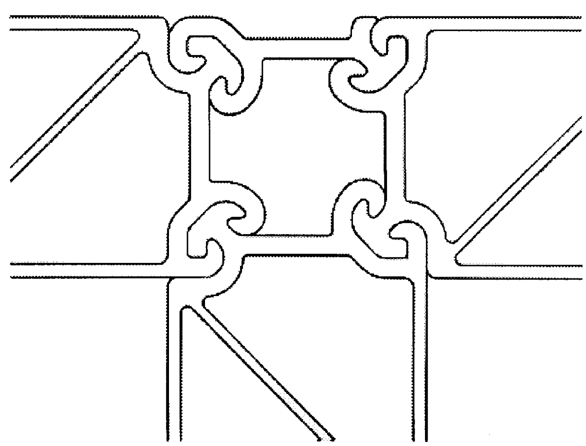


Fig. 5.16: The spread barb joint is used when the nominal barb thickness is less than one-tenth the joint region size. Barb features are moved outward to maximize moment resistance.

The spread joint can also be offset to further widen the barb stance, if panel surface flushness is not required. Care must also be taken to prevent an excessively large flexural region.

Integral Trussed Panel Versus Clip-on Designs

Up to this point, all of the figures except for Figs. 5.12 and 5.13 have been depicted as panels with truss structures within each panel. The advantages of an integral trussed panel include: one whole part, no required assembly, smooth continuous panel surface. Fig. 5.17 shows the cross-section of a Cubbeez™ panel having eight trussholes within its integral trussed structure.

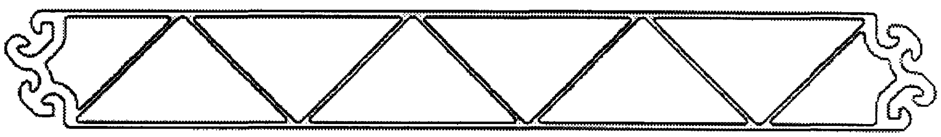


Fig. 5.17: The Cubbeez™ panel features an integral trussed panel structure to provide high stiffness-to-weight with no required assembly.

Figs. 5.12 and 5.13, however, are shown as solid panel sections connected to end clip joint elements called Clippeez™. A cross-section of a Clippeez™ panel is shown in Fig. 5.18. For prototyping purposes, and for customers wanting specific panel widths, separate end clips allows for any board or panel of appropriate thickness to be attached to end clips.

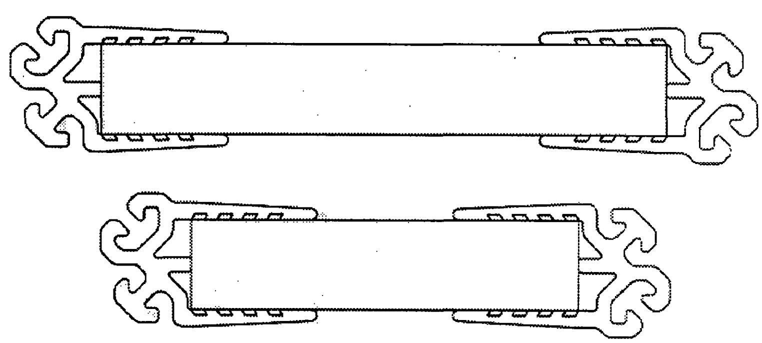


Fig. 5.18: Clippeez™ end clips can be attached to boards of any width for customized storage system geometries.

As is discussed in Section 5.1.5, the decoupling of the end joint from the panel wall component enabled the designers to more expediently prototype the cubby system concepts.

Rotationally-Symmetric Truss Design

A rotationally-symmetric trussed panel is desirable because of its identical form when rotated 180° about its panel cross-sectional axis as identified in Fig. 5.19.

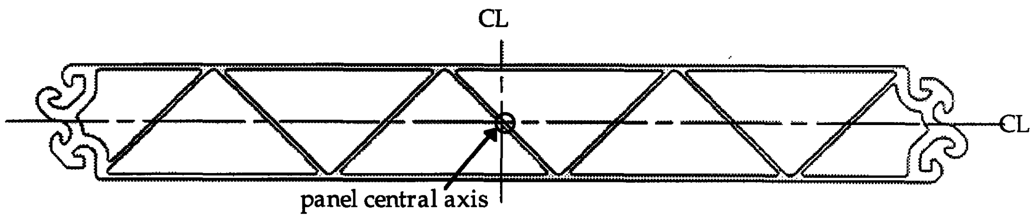


Fig. 5.19: A rotationally-symmetric trussed panel can be rotated by 180° about the panel central axis and result in the identical geometry.

By keeping the panel symmetric in this fashion, the truss-to-end design is consistent on both ends, preventing structural properties from being different on one end to the other. The trussholes also remain in place relative to the panel and the cubby system, the significance of which is explained below regarding plug-ins. Fig. 5.20 below would not appear different if either a panel were rotated or if the entire cubby unit were rotated about a cross-sectional axis ("into the page" axis).

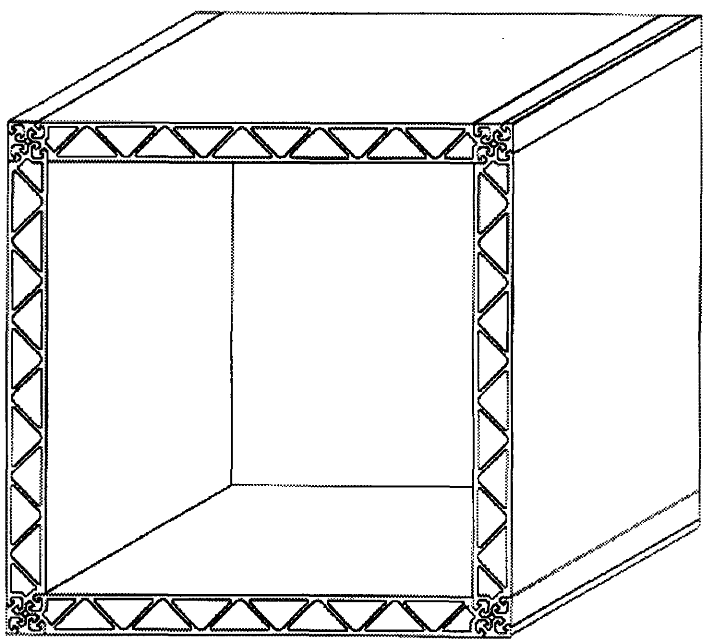


Fig. 5.20: Close inspection of the panel cross-section reveals that rotation of a panel or of the unit cubby itself by any multiple of 90° about the cross-sectional axis ("into page") results in an identical cross-section.

This symmetry is especially important in the design of fractional panels, as these fractional panels should also exhibit the same 180° identity property for use of plug-in accessories. For example, Fig. 5.10, shown again as Fig. 5.21 below, is composed of rotationally-symmetric panels. Rotation of any full or fractional panel would not change the appearance of the structure, just as the unit cubby in Fig. 5.20 does not change. All of the triangular trussholes would be in the same orientation as another above or below in other panels.

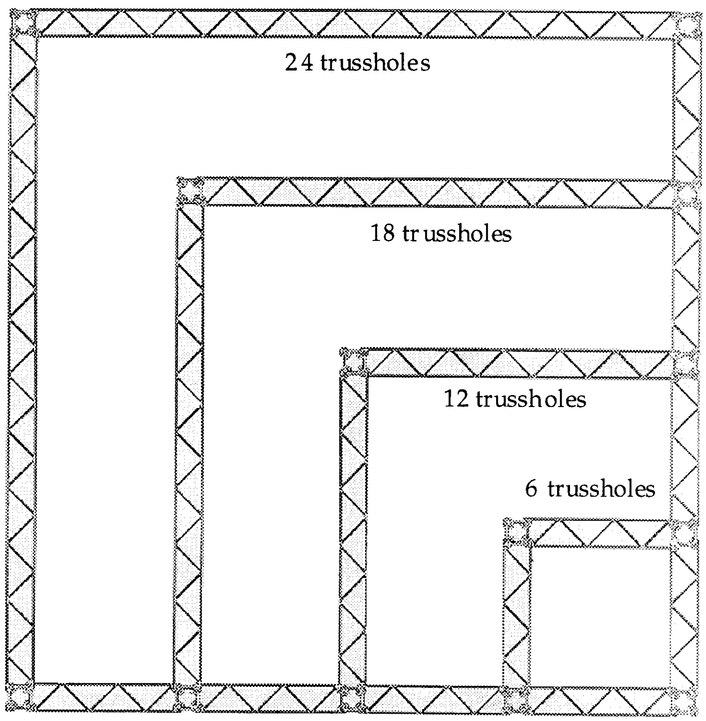


Fig. 5.21: Quarters fractional panels of full, three-quarter, one-half and one-quarter widths are all rotationally-symmetric with themselves and maintain trusshole symmetry and alignment throughout the system.

Given a scheme for fractional panels (e.g. halves, thirds, quarters), the smallest fractional panel must include an even number of trussholes (e.g. 2, 4, etc.). This condition ensures that all of the panels have even numbers of trussholes and retain the rotationally-symmetric properties, as well as the structural consistency at the joint ends.

For the example in Fig. 5.21, the full panel has 24 trussholes; three-quarter panel: 18; half panel: 12; quarter panel: 6. If a thirds fractional scheme were chosen, the fractional panel set would have 24, 16 and 8 trussholes, another valid design set. However, the panels in Fig. 5.20 have 12 trussholes. If these panels were designated as the full-width panels, then only a halves or a thirds fractional scheme could be used. A quarters fractional scheme would result in the one-quarter panel having 3 trussholes, upsetting the symmetry condition of even number trusshole count.

Plug-ins

Given a consistent and symmetric scheme of trussholes in a cubby system, plug-in accessories can be added. Doors, back plates, dividers, and drawer assemblies, for example, using plugs designed to fit within the trussholes allow the cubby system to be used in greater ways.

Fig. 5.22 shows three types of plugs that can fit within trussed panels. The corner plugs fit within the acute corners of a trusshole, and may be used in pairs, within the same trusshole or in two distinct trussholes, to fix the corresponding accessory in place. The other two plugs shown, the V-plug and the rounded square plug, may be used in any general truss design; however, in order to maintain the coincidence of the plug center (in the case of the square plug) with the midline of the panel, the truss design must be altered slightly. This feature becomes important for accessories made for geometric generality; that is, the accessory need not be affixed in only one orientation.

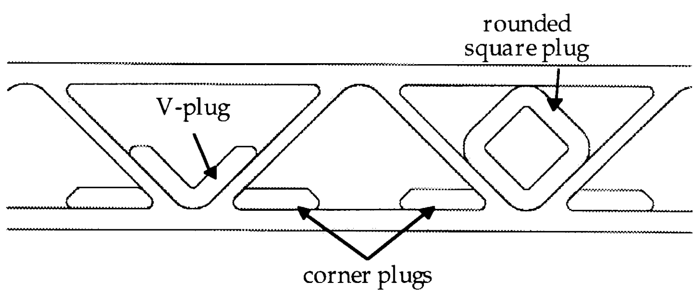


Fig. 5.22: Three types of plugs that fit into trussholes: corner plugs, V-plugs, and rounded square plugs. V-plugs and rounded square plugs need an altered truss design to retain consistent placement relative to the panel midline.

For example, plug-in dividers are depicted in Fig. 5.23. Whether the dividers are single-centered, double, or single-offset, each end of the divider features a pair of corner plugs like those of Fig. 5.22. These dividers may be positioned at any location within the cubby space at regular intervals, in either a vertical or horizontal orientation.

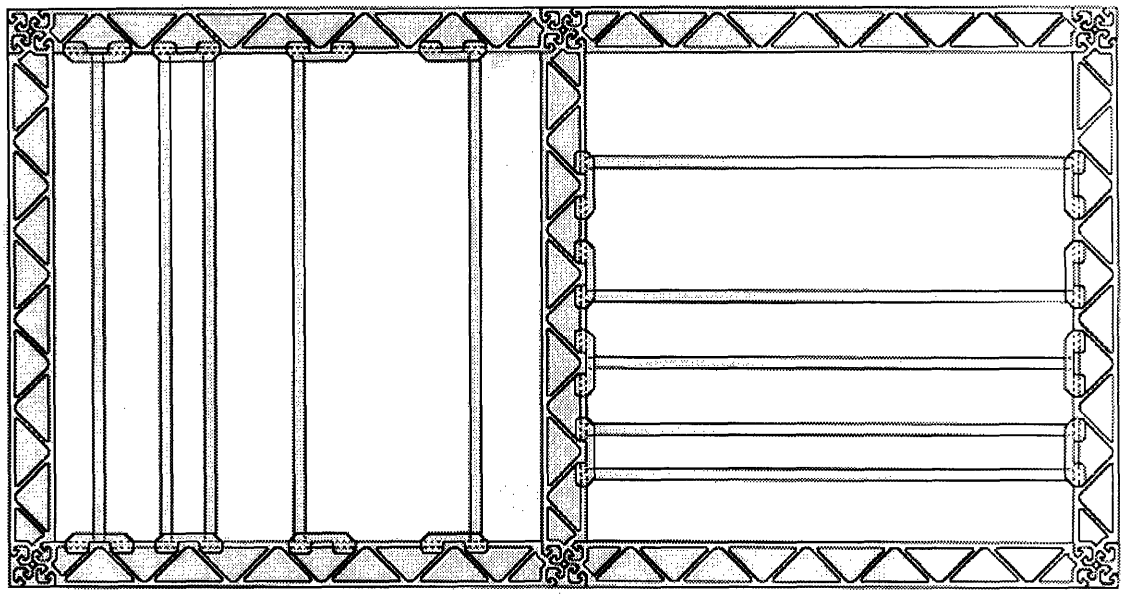


Fig. 5.23: Plug-in dividers can be added to cubbies by inserting plugs into the cubby panel trussholes at any of the regular trusshole intervals. Note that the same dividers can be used horizontally or vertically.

See Appendix B (patent application, discussion of the invention) for more information and other examples of plug-in accessories.

Approximate Trusses

Approximate trusses are used in the modular storage systems for two main purposes:

1. Greater variety of plug-in accessory designs:
   - An approximate truss creates trussholes with major corner fillets that are tangent with the long side of the trusshole.
   - Special plugs, like the V-plug and rounded square plug in Fig. 5.22, maintain position along a panel's midline in all of the trussholes.
   - Plug-in accessories can then be designed without orientation limitations.

2. Greater customization of cubby structure dimensions:
   - In a normal truss, trusshole center-to-center distance L is well-defined, but inflexible to customization. In an approximate truss, the center-to-center trusshole distance may be increased by up to one wall segment thickness, providing a design degree of freedom.

- The choice of center-to-center distance multiplied by the number of trussholes allows the overall panel dimensions to more closely fit other geometric requirements of a cubby storage application.
- The trade-off in moment of inertia (and corresponding stiffness and panel deflection) may be offset by gains in satisfying other customer requirements.

In a standard truss design, the midlines of the truss members are coincident with the midlines of the outer wall members, as shown in Fig. 5.24.

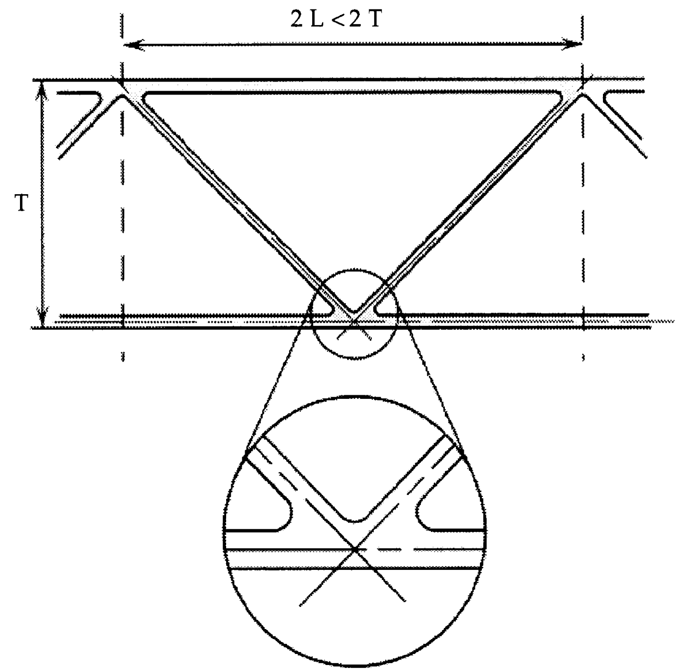


Fig. 5.24: A standard truss features the midlines of the truss segments intersecting at the midline of the outer wall segment.

Given a 45° truss angle (the angle between the outer wall segment and the truss segment), the trusshole center-to-center distance is fixed for a given panel geometry. For a overall panel thickness T, the center-to-center distance between adjacent trusses (or trussholes) L is equal to:

$$L = T - t(wall) \qquad \text{(E5.2a)}$$

Thus, as shown in Fig. 5.24, the center-to-center distance between similarly-oriented trussholes is:

$$2\ L = 2\ T - 2\ t(wall) < 2\ T \qquad \text{(E5.2b)}$$

However, in some cases, the midline coincidence condition may be dropped to produce an *approximate truss*. In an approximate truss, the truss segment midlines are not coincident with the midline of the wall segments. Fig. 5.25 shows the intersection of truss midlines intersecting at the outer edge of the outer walls, an offset of one-half the outer wall segment thickness. Offsetting the intersection more than that amount is not recommended due to the excessive resulting loss of panel stiffness.

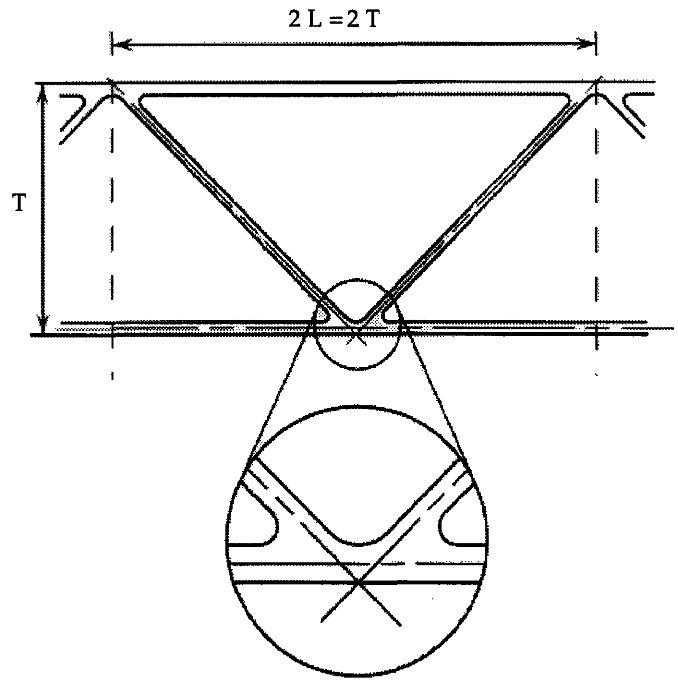


Fig. 5.25: An approximate truss can extend the center-to-center distance between trussholes without increasing the overall panel thickness or the truss angle. In this figure, the truss segment midlines intersect at the outer edge of the wall segment.

While this creates a flexural region on the order of the wall segment thickness *t(wall)*, a panel width can be increased up to about one wall segment thickness *t(wall)* per trusshole. Thus, the center-to-center distance between neighboring trussholes in an approximate truss can take on a range of values:

$$T - t(wall) < L \leq T \qquad \text{(E5.3a)}$$

The resulting center-to-center distance between like-oriented trussholes is thus:

$$2\,T - 2\,t(wall) < 2\,L \leq 2\,T \qquad \text{(E5.3b)}$$

Fig. 5.25 shows an approximate truss with the truss intersection at the maximum recommended offset such that $2\,L = 2\,T$.

Another method of extending the panel width without changing the overall panel thickness T is to change the truss angle θ. Decreasing the truss angle has similar effect on panel stiffness and corresponding panel deflection.

For applications where the geometric constraint of panel width, panel thickness, wall segment thicknesses and trusshole count is unacceptable, the approximate truss design removes some of the constraint by allowing the trusshole center-to-center distance to "float" or vary slightly in order to meet panel width requirements. Care should be taken when implementing the approximate truss design as the flexural region may lead to excessive panel deflection or buckling under sufficient loads.

For some types of plugs, including the V-plug and rounded square plug of Fig. 5.22, the design of the truss is important. If the fillet of the major corner of the trussholes is not tangent to the inner surface of the wall segments, then a rounded square plug's center will assume different positions in alternating trussholes, neither coincident with the panel midline. This alignment condition guarantees that an accessory such as a cubby face plate employing rounded square plugs can be inserted into the trussholes in any 90° or 180° rotation without concern for a "correct" orientation.

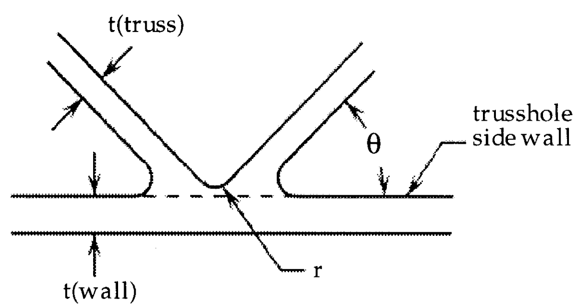


Fig. 5.26: The fillet radius r at the major trusshole vertex can often not be made tangent to the side wall line of the trusshole from either geometry or manufacturing limits.

Referring to the standard truss design of Fig. 5.26, for some ratios of truss segment thicknesses and outer wall thicknesses, the fillet radius r^* in a standard truss can be tangent with the trusshole side surface. Tangency is possible when:

$$t(truss) < t(wall) \cos \theta \tag{E5.4}$$

If Eqn. E5.4 is true, then fillet tangency occurs for a certain value of r^*:

$$r^* = \frac{t(wall)\left(\cos\theta - \frac{t(truss)}{t(wall)}\right)}{2(1-\cos\theta)} \quad \text{(E5.5)}$$

Manufacturing limitations, however, may make the required fillet radius in a standard truss impractical or impossible to produce. For example, cooling considerations require inner trusswalls to be about 70% as thick as the outer walls so that all segments cool at about the same time. For $\theta = 45°$, $\cos\theta = 0.707$, so Eqn. E5.4 cannot be satisfied with a thickness ratio over 70.7% with any fillet radius. With a 70% ratio, however, the required fillet radius would have to be 0.012 *t(wall)*, by Eqn. E5.5. For *t(wall)* = 0.050", the fillet radius would be 0.0006", which is essentially a sharp corner. Such a small fillet on a plug may cause high contact stresses on the truss-wall intersection region, which risks damaging the trussed panel material and overall panel integrity.

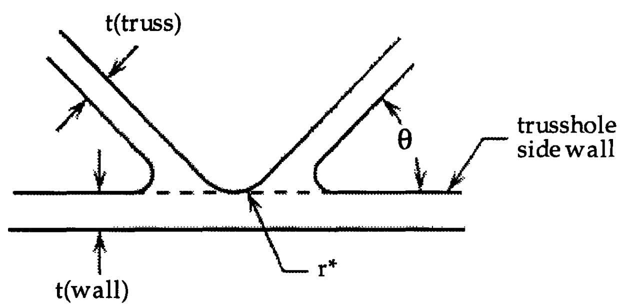


Fig. 5.27: Approximate truss design showing a fillet radius r^* which is tangent to the side walls of adjacent trussholes.

In an approximate truss, depicted in close-up in Fig. 5.27, where the truss segment midlines intersect at the outer surface of the panel (maximum recommended offset), trusshole fillet tangency is possible when:

$$t(truss) < 2\, t(wall) \cos\theta \quad \text{(E5.6)}$$

When Eqn. E5.6 is true, then fillet tangency occurs for fillet radius r^* of:

$$r^* = \frac{t(wall)\left(\cos\theta - \frac{t(truss)}{2t(wall)}\right)}{(1-\cos\theta)} \quad \text{(E5.7)}$$

Comparing Eqn. E5.6 with Eqn. E5.4 shows that the approximate truss accommodates twice as large a range of truss segment thicknesses for which fillet tangency is possible.

Other embodiments are included in the invention and can be found in Appendix B, the patent application text and figures.

5.1.4 The Patent Application Process

Background Discussion of Patents

When designing solutions, it is good practice to determine what already exists, in old and current products, and in issued patents and prior art. In development and marketing, protection of the new designs and the intellectual property is also essential. While other options of protection involve copyrights and non-disclosure (trade secrets), the patent remains as an effective tool in protecting designs and inventions. A patent also serves as an enabling tool towards development and marketing, especially when outside firms and companies are to be contacted.

It is common practice and policy in the United States and abroad for companies not to accept solicitations for work on designs without at least a pending patent status. The reason cited for this requirement is to legally protect the inventor and the company from controversy that may arise from misunderstandings or misinterpretations between parties. Patent infringement is a risk in development, and legal measures to debate or refute infringement is costly, so companies preempt these situations by setting stringent policy. In addition to a filed patent application, a nondisclosure agreement is usually required between a company and the inventor.

When a patent is filed, a patent examiner at the United States Patent and Trademark Office (USPTO) is assigned. The examiner reads the application and compares the concepts and claims to issues patents and any prior art or public knowledge. If there is evidence that the patent application concepts are not original or not distinct from prior patents, the examiner will reject the application.

The applicant may then revise the application to remove claims and concepts that the examiner rejects, or to send a rebuttal to the examiner clarifying why the objection is incorrect or unfounded. This procedure may occur a few times, after which the examiner either deems the application is acceptable for patent issue, or finally rejects the application. In the latter case of rejection, an applicant has options to dispute the rejection in court; however, usually the final decision of the examiner is accepted by the applicant.

Almost six million patents have been issued by the United States alone, nearly 120,000 issued per year in recent years. This volume of applications and the research that must be done by examiners means the patenting process can take years. In addition to the time spent on patent application preparation, examiner review and applicant rebuttal, the cost can also be a barrier. Although the filing fee is only a few hundred dollars, the fees for a patent lawyer to refine the application and to rebut any examiner's objections can easily reach thousands of dollars.

However, once granted, a U.S. Patent provides the inventor or invention assignee exclusive rights for twenty years from the date of filing. Generally speaking, these rights allow the inventor a monopolistic use of the intellectual property, and including the right to seek damages or compensation from any infringer of the patent.

The Patenting Process for Modular Storage Systems

Applying for a patent involves several stages including:

- Background research of issued patents and prior art
- The patent application
    - Explanation in concise and specific terms the concepts and designs to be patented
    - Discussion of how the invention differs from prior disclosures.
    - Figures and drawings with numerical annotations for graphical to assist in relating figures to text
    - A list of claims determining the breadth and scope of the invention, and thus defining the domain of intellectual property at stake
- Conversion into legally-accepted terminology
- Payment of associated patent lawyer fees
- Submission of signed application
- Payment of application
- Rebuttals in response to examiner rejections

While some patent applications can take as little as days or weeks to prepare following invention, the modular storage system project was different. In this case, the patent application process stretched well over a year in development. In September 1995, Prof. Slocum had a draft of "Modular storage system and components." When this thesis author became a partner in the effort, the process included four more months of related invention and design, in addition to the addition and revision of the initial version of the application.

From September to December 1995, the scope of the invention expanded multifold, with the explanation of the invention more than tripling in length and the number of figures increasing fourfold. Hundreds of issued patents were reviewed in the *Official Gazette*, on online patent abstract databases, and on microfilm at the Boston Public Library. Nearly ninety patents were cited in the application as related but different inventions. A list of these reference patents is given in Appendix A.

Prof. Robert Rines, founder and patent lawyer of Rines & Rines, a Boston and New Hampshire firm, received the new application draft and copies of each reference background patent. Terminology and grammar were modified to more legally-appropriate language. In February 1996, the patent application was filed with the USPTO entitled "Modular storage system, components, accessories, and application to structural systems and toy construction sets and the like." Appendix B includes the write-up and figures of the patent application, excluding the 35 claims. At the time of this thesis writing, the U.S. Patent application is still under examination.

One year later, in February 1997, a Patent Cooperation Treaty (PCT) was filed to provide international patent protection.

5.1.5 Prototyping & Proof of Concept

Waterjet-cut Profiles

Two methods were used to test the concepts of the axisymmetric barb joint and the modular storage system. The first physical evaluation of the joint design required the use the abrasive waterjet-cutter machine situated in MIT Building 35 machine shop. These waterjet-cut profiles were cut out of various materials such as phenolic, plastic, wood and aluminum. Typical thicknesses were kept at 0.25″ thick to minimize taper effects resulting from the cutting process.

Fig. 5.28 shows some samples cut with this method. The top item is an integral trussed profile made from 0.25″ thick 2024 aluminum. Note that the truss members are quite thin, with the overall trusses region being only 0.75″ high, and a joint region of 1.00″ in characteristic dimension. The set of pieces in Fig. 5.28 are prototype end clip profiles made of ABS plastic and aluminum. The pieces fit with minimal clearance, and were used to illustrate critical mating surfaces and compliance effects.

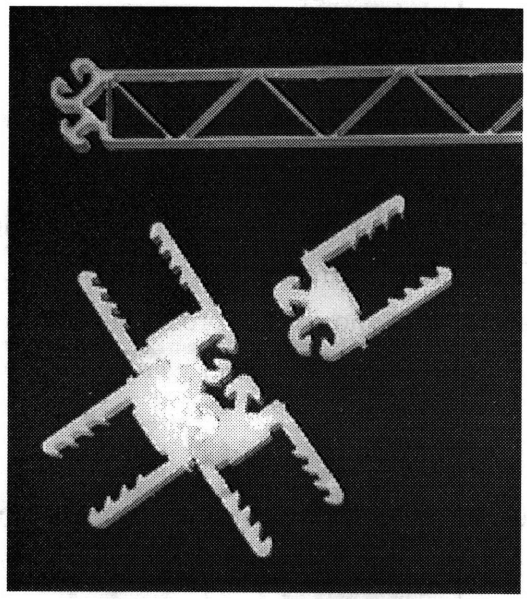


Fig. 5.28: Prototyping the barb joints implemented the waterjet cutter to produce these 0.25″ inch deep samples.

Since the profiles were essentially two-dimensional, a real-size three-dimensional prototype was needed. The standard cross-section and the material choices pointed to plastic extrusion as the logical choice.

Custom Extrusion of End Clips

The next step of prototyping involved actual manufacture of parts to demonstrate the modularity in storage system assembly and disassembly. As mentioned in Section 5.1.3, the designs included an option to use the end joint features decoupled from the panel wall component. This feature proved crucial to the prototyping of the project, and the Clippeez™ end clip embodiments were tested. Fig. 5.29 illustrates a corner joint using the Clippeez™ system to be tested with actual plastic extrusions. The end clips would be attached to the ends of boards or panels, and the storage system could be evaluated.

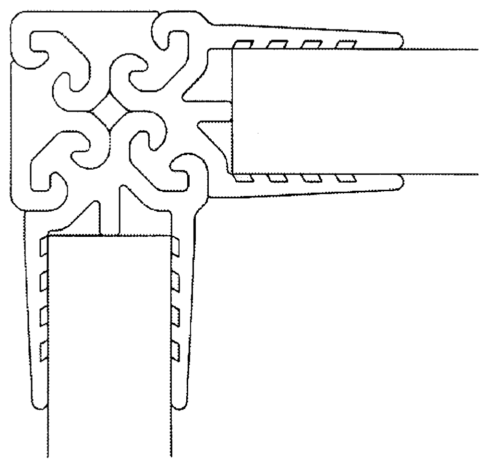


Fig. 5.29: Drawing of the anticipated corner joint using Clippeez™ end clip extrusions.

Two company partners were used for this stage, for tooling and for manufacture. Tooling was done by Charmilles Technologies, in Owosso, MI. Charmilles contributed its electro-discharge machining for no cost in producing two sets of die plates. Using wire EDM, two sets of die plates of 0.50" steel were made, for the clip design and the terminator shape.

At the same time, extrusion direction was supplied by Barbour Plastics, of Brockton, MA. With their advise regarding die drawdown and other extrusion effects, the desired end product drawings were modified to take into account these effects, and the designs were sent to Charmilles in standard .dxf CAD format. In September 1996, Barbour extruded the first lengths of end clips and terminators from rigid polyvinyl chloride (PVC) with 5% PVC regrind.

The first set of extrusions were evaluated; the joint concepts were proven feasible. A second extrusion run was scheduled for November 1996, at which time additional post-extrusion tooling would be ready. Prof. Slocum and this thesis author were present to guide in the extrusion process and the real-time modifications.

Figs. 5.30 through 5.34 show the major steps of the custom extrusion process. For low volume runs such as this one, precision post-extrusion tooling was not used. In Fig. 5.30, molten PVC plastic leaves the extruder and die plate. The shape is approximately 10% larger than the desired size, as the plastic will shrink during cooling. Fig. 5.31 shows the guide plates over which the still-pliable extrusion will ride to minimize excessive twisting and deformation during cooling. Fig. 5.32 shows the simple post-extrusion tools used to guide the end clip barb features from deviating from desired geometry. The weight of the plastic causes unsupported features to sag in nonuniform ways; hence, the guiding finger-like instruments are empirically adjusted until the extrusion is acceptable. Fig. 5.33 shows the numerous fans used to air-cool the extrusions. For other extrusions, a water bath can be used, but in this case, slow cooling by forced convection of air would minimize warping effects and internal stresses over the length of extruded product. Fig. 5.34 shows extrusion product cooled enough to be cut with the automated saw.

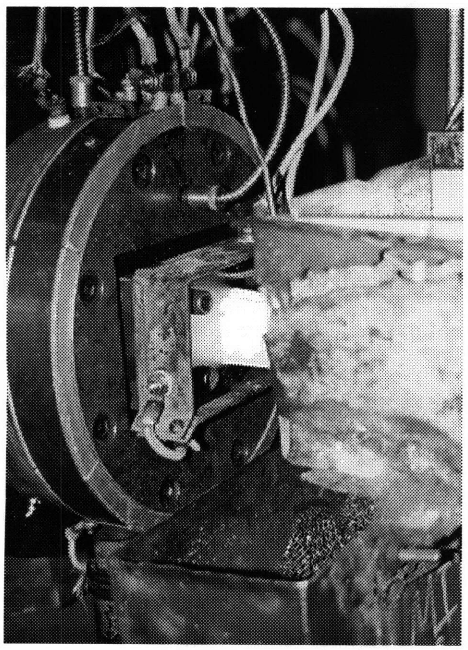


Fig. 5.30

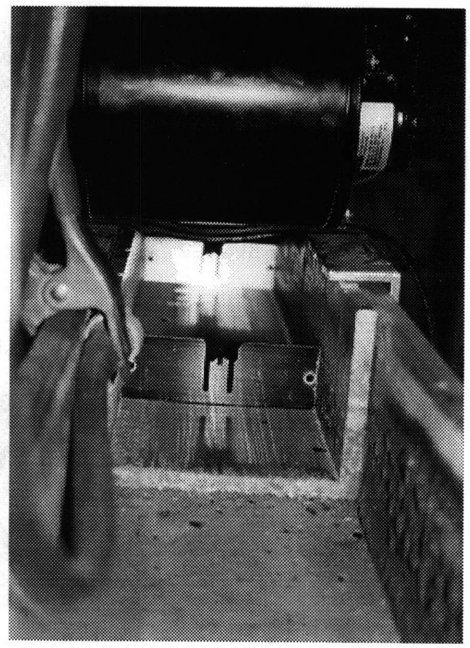
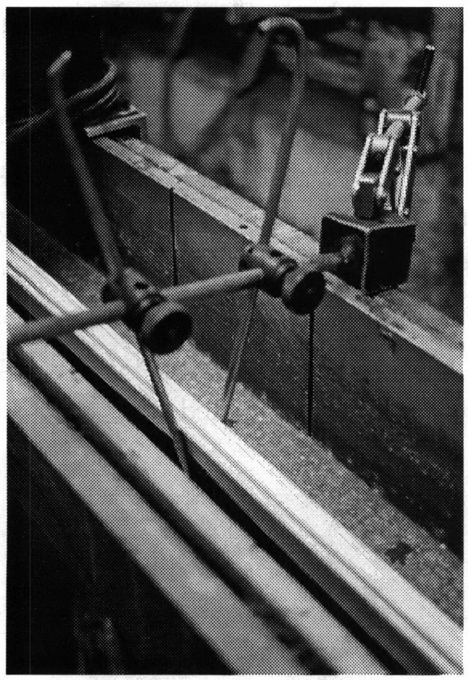


Fig. 5.31

Fig. 5.30: Molten PVC exits the die plate at approximately 10% oversize.

Fig. 5.31: The extrusion rides over guideplates for the lower end clip jaw arms, to minimize excessive deformation during cooling.



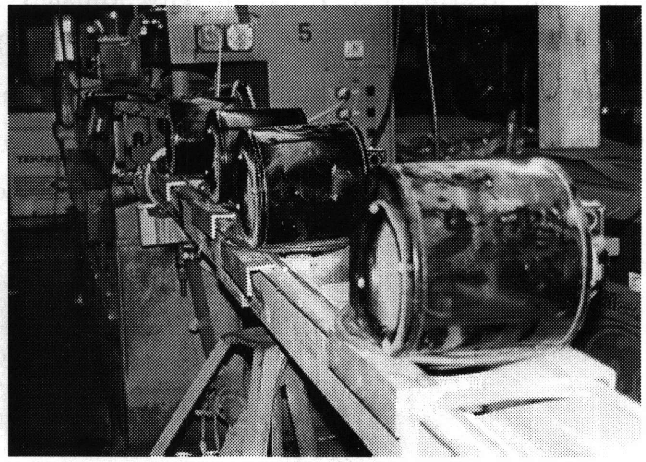


Fig. 5.32 Fig. 5.33

Fig. 5.32: Simple finger-like tools are positioned along the cooling path to "nudge" the molten extrusion into desired position. An empirical process, the desired features are still produced.

Fig. 5.33: Numerous fans blow air over the extrusion to cool the material. Excessive cooling rates would cause greater warping in the length of the extrusion.

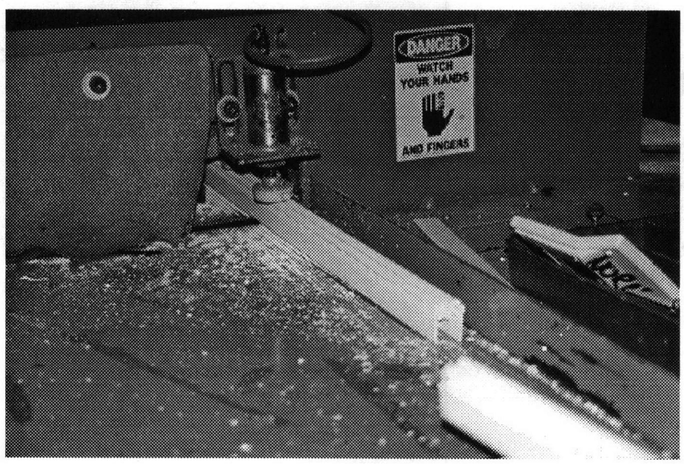


Fig. 5.34: With the extrusion cool enough to touch, an automated saw cuts the extrusions to desired lengths.

Extrusions cost approximately $0.46 per linear foot for the end clip, and $0.32 per foot of the terminator. This is based upon cost of material (virgin rigid PVC) and manufacturer markup. In addition, 10 hours of engineering time for set-up and tooling were required.

Comparison of Extrusions with Designs

Fig. 5.35 shows the desired extrusion geometry (Fig. 5.35a) with a cross-section from extruded product (Fig. 5.35b). Notice the significant deformation of the features. The shape in Fig. 5.35 is shown in the same orientation as the die plate on the extruder. Thus, it can be discerned that the sagging effect from the weight of the extrusion material, coupled with the simple post-extrusion tooling, resulted in the changes in shape.

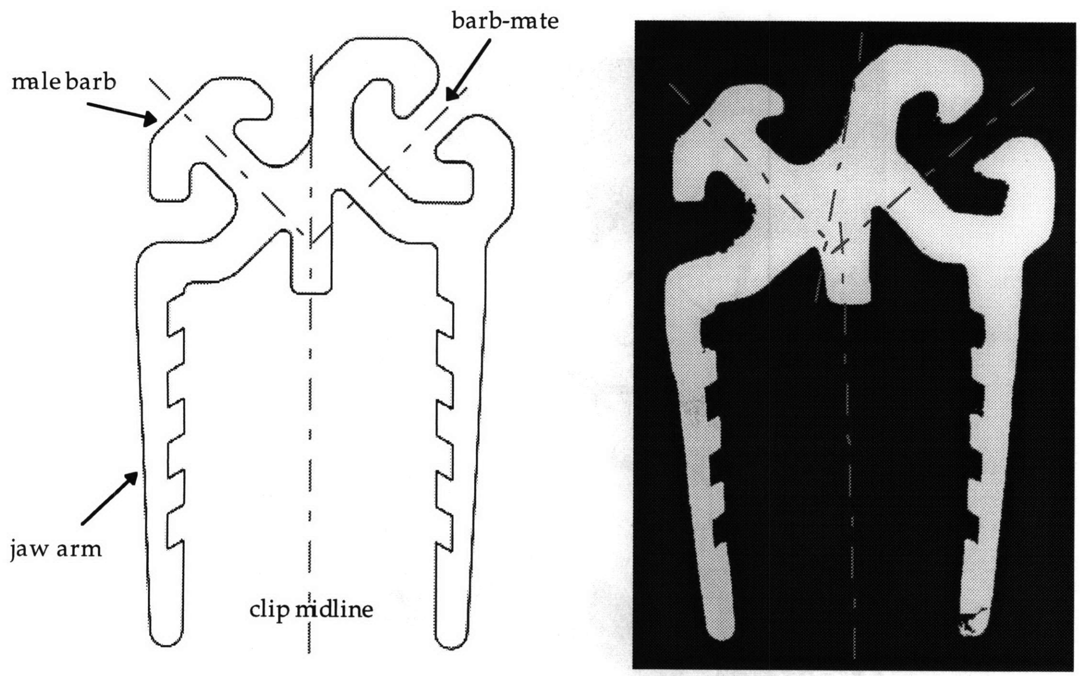


Fig. 5.35a Fig. 5.35b

Fig. 5.35a: The desired extrusion geometry of the Clippeez™ end clip. The actual die plate upscaled the shape by a 10% drawdown factor as well as 0.010" clearance offset from the male barb. Fig. 5.35b: A cross-section from extruded end clip. The jaw arms closed during cooling. The barb and barb-mate arms also sagged downward during cooling because of their weight.

The design of the joint calls for a 90° spread angle between the barb centerline and the barb-mate centerline. The extrusions exhibited spread angles from 93° to 97°. Hence, the minimum summation of spread error for four joints would be 12°, while the maximum total error could be on the order of 28°. There is also slight angular error between the intended clip midline (vertical in Fig. 5.35a) and the resulting midline between the barb and barb-mate.

In addition to the visible differences between Figs. 5.35a and 5.35b, the extrusions also exhibited warping over the length of the extrusion. For a three foot length of extrusion, there was about one inch of warp, as a result of the greater cross-sectional area in the upper barb region contracting greater than the jaw arms of the lower half.

Despite the relative simple tooling and the deformation of the end clips during cooling, the end clips still interlock well enough to demonstrate the four-fold rotationally-symmetric joint design. Fig. 5.36 shows a cross-section of four end clips interlocking. Given the 0.010" offset of the barb surface from the ideal zero-clearance geometry, plus some elastic averaging and compliance in the joint, the four elements slide together with relative ease over one foot extrusion lengths.

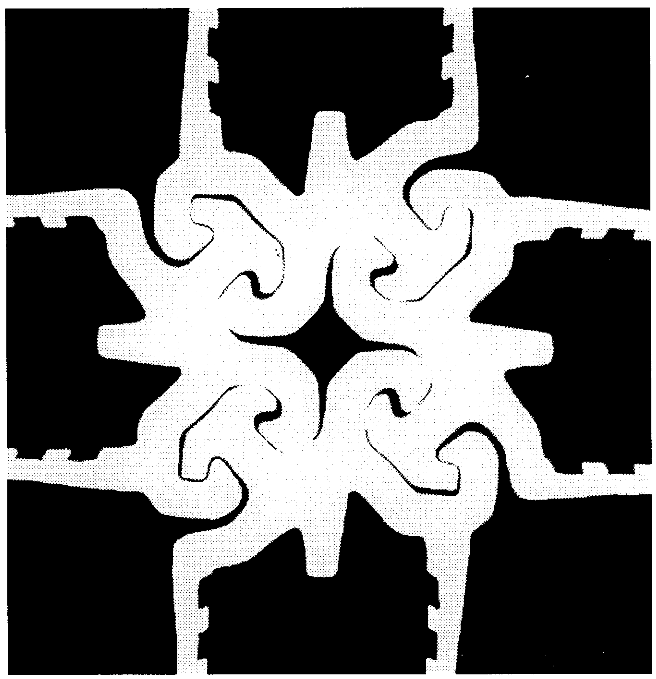


Fig. 5.36: A cross-section of four interlocking extruded end clips. The errors in spread angle (angle between barb and barb-mate), extrusion length warping and other manufacturing effects are accommodated by the designed clearances and by material compliance.

With better cooling controls and precise post-extrusion tooling and guides, which would be standard practice in larger extrusion runs, the joint features could be held to tighter tolerances. This improvement in spread angle and a decrease in extrusion length warping will also allow the designed clearance between mating surfaces to decrease, resulting in a stronger joint.

The terminators, shown in Fig. 5.37a and Fig. 5.37b, the intended design and the extruded cross-section respectively, exhibited less overall deformation during extrusion.

Fig. 5.37a shows the intended terminator design with the male barb and the barb arms of the female barb-mate. Fig. 5.37b shows a cross-section of the extruded product. The extrusion exhibits a blight deviation from the desired 90° spread angle; samples were measured with spread angles between 91° and 93°, less error than in the end clip extrusions. The slight angular error between the terminator vertical midline and the actual midline between the barb and barb-mate is of a few degrees, but this error manifests itself in the prototyped systems in minor fashion since there is no board or panel attached to the terminator.

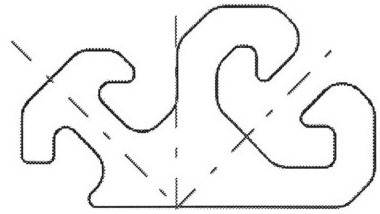


Fig. 5.37a

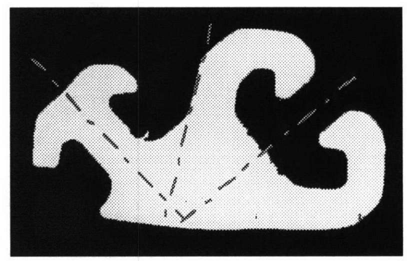


Fig. 5.37b

Fig. 5.37a: The terminator design features only the male barb and the barb arms for the female barb-mate. Fig. 5.37b: A cross-section from the extruded terminator shows shape errors, including bulging at the base of the terminator from sagging, and slight angular spread of the barb and barb-mate.

As the spread angle is closer to ideal, the terminators fit more easily into any joint set as the designed clearances need not accommodate as much spread angle error as in the end clip extrusions.

Prototyped Clippeez™ Systems

Once the prototype end clips and terminators were extruded, Clippeez™ systems were assembled and tested to simulate Cubbeez™ storage systems. Fig. 5.38 illustrates various embodiments of the system.

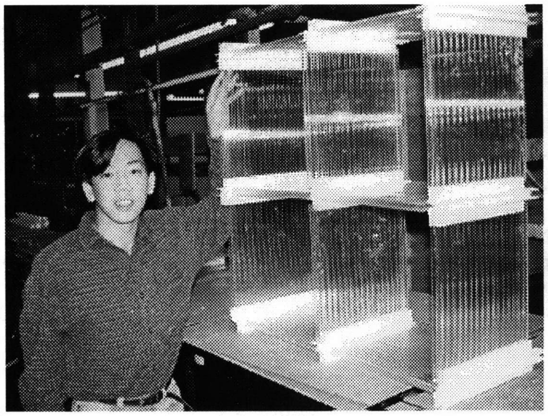


Fig. 5.38a

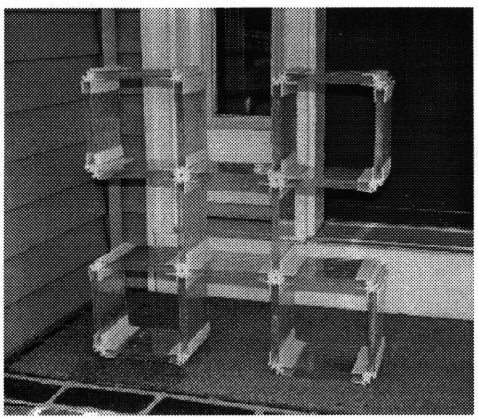


Fig. 5.38b

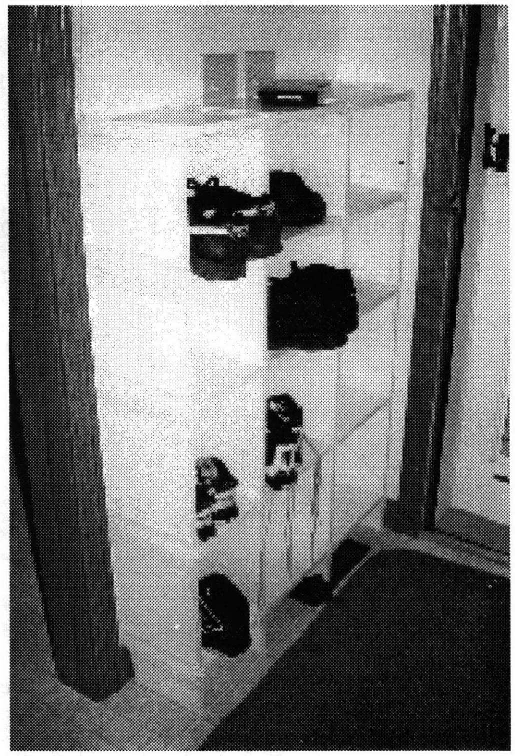


Fig. 5.38c

Fig. 5.38a: Thesis author and co-inventor Christopher Ho displays full-size Cubbeez™ mockup made from Clippeez™ end clips and clear polycarbonate twin-wall panels. Fig. 5.38b: Mini-Cubbeez™ prototype in an "X" configuration. This structure is not recommended for large loads due to the lack of side panels. Fig. 5.38c: Prototyped storage system in the home of Prof. Slocum, used for shoes in the hallway.

5.1.6 The Search for a Market In

Finding a sponsor or licensee for the product concepts required multiple attempts in various market niches. As the product concepts can be applied to different industries and with different materials, an extensive information gathering search was conducted in parallel with the submission of the innovation to prospective sponsor companies.

Requests were made to companies for:

- Information: details regarding the manufacturing, materials and market factors that affect the detailed designs of the modular storage system.

- Potential licensing: submission of the storage system concepts for adoption by the company or a collaboration agreement to further develop the project.

Below is a list of companies contacted in developing the Cubbeez™ project. Each company contact contributed to the information base of the thesis author, and in many cases led to a deeper discussion of the project as new product concept.

Plastics Extruders

Barbour Plastics
Certified Thermoplastics
Condale Plastics
Keller Products
World Plastic Extruders

Plastics Developers and Suppliers

Commercial Plastics
Hoechst Celanese
Trexel
Rohm

Aluminum Extruders and Manufacturers

Alcoa
Alexandria Extrusion
AMCO
General Extrusion
Magnode
Technical Dynamics Aluminum
Superior Metal Shapes

Machine and Tooling Developers

Charmilles Technologies
HPM

Similar Product and Process Companies

CertainTeed
Georgia-Pacific
Weyerhauser

Retailers and Corporations

Akro-Mils
Home Depot
Home Quarters
IKEA
Lego
Rubbermaid
3M
Wal-Mart

Contacting these various companies addressed the following major issues:

- Manufacturing process selection
- Material selection
- Competitive and related products
- Complementary product lines
- Cost of manufacturing
- Consumer price goals
- Demand for various design embodiments
- Sizing of design embodiments

Each of these areas influenced the joint and truss detailed designs for the different configurations for different markets. Only when a company expressed interest in the fundamental innovations were the designs modified more in detail.

Firms to which product sheets were sent fell into various categories:

1. Companies producing similar or complementary products: Akro-Mils, 3M, Lego and Rubbermaid, for example, produce various forms of organizational products and items which would be complemented by the Cubbeez™ modular storage systems.
2. Companies using competing materials for competing products: Weyerhauser uses wood and paper for various products, including storage system materials.
3. Companies using similar materials: Rubbermaid is one of the largest producers of plastics for consumer products, yet does not support extrusion in its production.
4. Companies using similar manufacturing processes: Georgia-Pacific and CertainTeed make plastic extruded vinyl siding products for the home-building market.
5. Companies selling and distributing related products: Wal-Mart and Home Depot regularly stock and retail products for home improvement and storage systems.

Interest by companies in Groups 1, 2 and 5 remained limited throughout the market search. For Group 1 companies, the Cubbeez™ design was liked by most, but was outside of the companies' existing product lines and distribution channels. For Group 2 companies, the material choice (plastic) often represented too great a difference to offer any support. Group 5 companies showed little interest in supporting new product development in its infancy.

In November 1996, a product sheet was sent to a manager in Sales & Marketing at Rubbermaid. Days later, the Vice President of Research and Development contacted this thesis author expressing interest in the Cubbeez™ product concept. Over the next five months, engineering, material, detailed designs and cost issues were discussed with engineers and managers at Rubbermaid assigned to project research. As discussed in more detail in following sections, these discussions led to detailed design of Cubbeez™ panels. Cost, the driving factor, requires proper selection of material and dimensioning of the panel cross-section.

As described earlier in this chapter, prototyping of the Clippeez™ end clip with tooling by Charmilles Technologies and custom extrusion in PVC by Barbour Plastics resulted in prototyped mini-Cubbeez™. These were also produced in November 1996, and a set was sent to Rubbermaid for their consideration.

As negotiations for a license for Rubbermaid were underway, submissions to other potential licensees halted temporarily. Terms for engineering time for development and a royalty schedule were considered in the first quarter of 1997. The main market niche for Rubbermaid is for garage storage. Household and office storage remain as other potential market niches.

In discussions with Rubbermaid, it became evident that Cubbeez™ would be a fundamental change in production capability. While the company is one of the larger manufacturers of injection molded plastics, extruded plastics represented a process for which the company had little experience or expertise. Rubbermaid looked to their internal sources and partner manufacturers for information. For the Cubbeez™ project, Prof. Slocum looked to Condale Plastics in the United Kingdom and then to Trexel, a local firm specializing in next-generation microcellular plastics, for plastics and extrusion advice, while legal advice came from Rines & Rines.

Along with Charmilles Technologies and Barbour Plastics, the network of companies working on the project continues to grow. This network of contacts include material sources, extruders, tool developers and marketing and business associates. For the continuing search for a market-in for this and other products, the network of companies willing to discuss new products and systems is essential for project development.

5.1.7 Current Status

At the time of this writing, Rubbermaid, Prof. Slocum and this thesis author are continuing to investigate ways to make Cubbeez™ panels cost-effective in various market niches. A key aspect of the project is finding a material and process inexpensive enough to meet what Rubbermaid deems is the maximum price for a storage system.

Other companies specializing in extruded panels, such as Rohm, a maker of multi-cavity polycarbonate extrusions for greenhouses and the like, are being contacted.

Trexel is considering the Cubbeez™ project for the application of microcellular plastic processes to reduce material use and thus cost by introducing microcellular voids in the plastic while still meeting strength and stiffness requirements.

5.2 Engineering & Design Details

This section describes the detailed development of the class of rotationally-symmetric joints, the integrated-truss panels, and the incorporation of manufacturing, engineering and non-technical issues on the designs.

5.2.1 The Rotationally-Symmetric Joint Class

The AxiBarb™ joint introduced in Section 5.1 is one specific embodiment of a larger class of joints, a new fundamental type of structural joints well-suited for the modular storage systems.

A Design Challenge

Fig. 5.39 shows four elements *1*, *2*, *3* and *4*, coming together in the joint region labeled as "?". This is a common situation for such applications where four walls or panels are to be joined at one location.

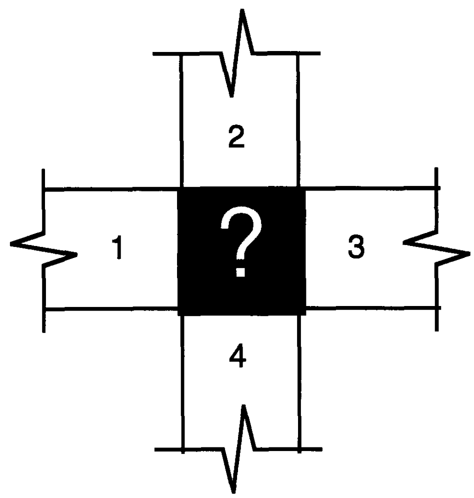


Fig. 5.39: A design challenge – joining four elements efficiently in the joint region.

The challenge is to design a two-dimensional (constant cross-section in the third dimension) structural joint that exhibits the following features:

- Efficient use of space and material
- Replicating and symmetric (identical features, identical elements)
- No centerpiece needed
- Structurally robust
- Resistant to tensile and bending loads
- Manufacturable by standard processes
- Applicable to systems joining any number of elements

Node Types and Grip Angle

Fig. 5.40 shows the four basic types of *node types*: stud, dovetail, tee, and barb. The single node joints can be characterized by the *grip angle*, the angle between the line of connection, or centerline, and the resisting contact surface. For the stud joint in Fig. 5.40a, the grip angle is 0°; resistance to pull-out comes strictly from friction and the compression of the stud in the stud socket. The dovetail, shown in Fig. 5.40b, has a grip angle of less than 90°, typically 30°, 45° or 60°. A tee joint, shown in Fig. 5.40c, nominally has a 90° grip angle, its resisting surface orthogonal to the line of connection. The barb of Fig. 5.40d has a back-angle, or a grip angle greater than 90°.

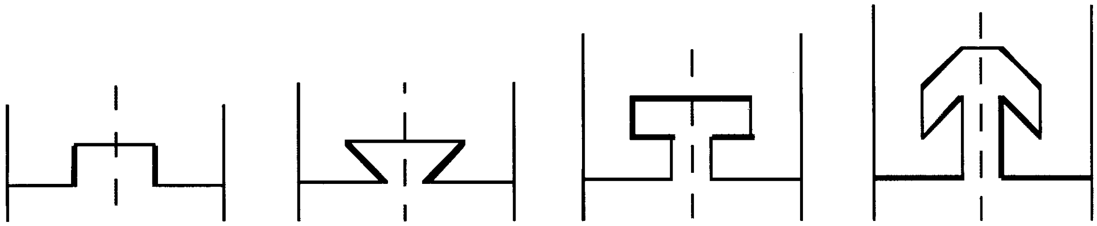


Fig. 5.40a Fig. 5.40b Fig. 5.40c Fig. 5.40d

Fig. 5.40: Common node types for joints: stud, dovetail, tee, and barb. These joints can be characterized by their increasing grip angle, and the corresponding increase in depth of penetration, and increase in mating surface contact.

As the grip angle increases, the depth of penetration of the protruding nodes into the mating element also increases. Similarly, the total mating surface increases. These effects can also be seen in Fig. 5.40.

These node types are important in the design and application of the new joint class, as they are well accepted and generally understood in the engineering and material communities. Applying them more effectively requires evaluation of existing joint designs.

The Existing *N+1* Joint Class

Fig. 5.41 shows two existing common joints, both belonging to the *N+1* joint class, so named because of one more piece (a centerpiece) is required to join the *N* elements (in this case, *N*=4). Fig. 5.41a shows the common single dovetail joint, in which four elements with dovetail features join together through a common centerpiece with corresponding mating features for the dovetails. Fig. 5.41b shows a common single barb joint, also using a centerpiece to accept the four elements' barbs.

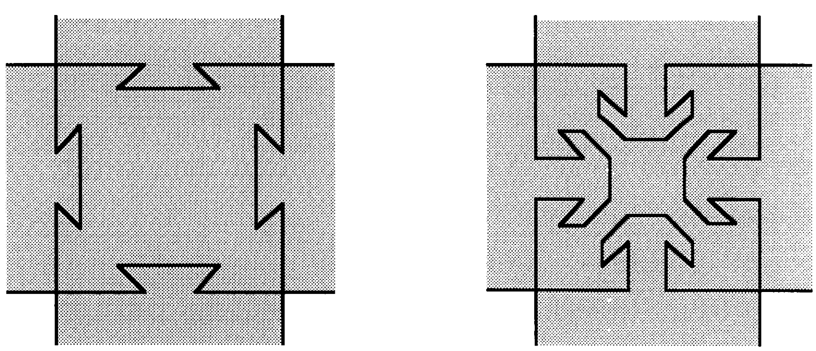


Fig. 5.41a Fig. 5.41b

Fig. 5.41a: The single dovetail joint of the *N+1* joint class. Fig. 5.41b: The single barb joint of the *N+1* joint class. Both joints use the joint region inefficiently and offer poor resistance to tensile and bending loads.

This *N+1* joint class does not satisfy all of the feature requirements mentioned previously. In particular, a fifth piece is needed to join four elements. The joint region is also inefficiently used; in the two examples in Fig. 5.41, the centerpieces' central and corner regions do not contribute significantly to the joint structure, wasting material with respect to the square joint region.

Also, the *joint stance* of the single features provide little resistance to moments. With the dovetail or barb along the midline of the element, a bending load is opposed with a moment arm of approximately half the element thickness, well below the maximum of the whole element thickness.

The Rotationally-Symmetric, or Axisymmetric, Joint Class

The new joint class that overcomes the disadvantages of the *N+1* class joints is represented in Fig. 5.42. These joints are called the *rotationally-symmetric,* or *axisymmetric, joint class.* In this joint class, the four elements are identical, interfacing along the diagonals of the joint region, shown as dotted lines in the figure. Each element's end features are identical as the element is repeated in a rotational fashion about the joint center axis; hence, the joints are axisymmetric. A straight arrow represents a node and its mating feature. The inner circular arrow represents the resulting closed *joint circle,* a distribution of loads throughout the joint.

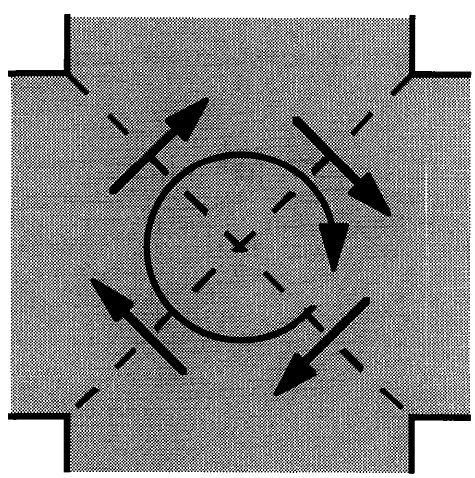


Fig. 5.42: The layout for the axisymmetric joint class. A closed force circle is formed with joint nodes located along the diagonals of the joint region.

Using the four basic node types described above, the four joints in the axisymmetric joint class are shown in Fig. 5.43 as the axi-stud, axi-dovetail, axi-tee and axi-barb joints.

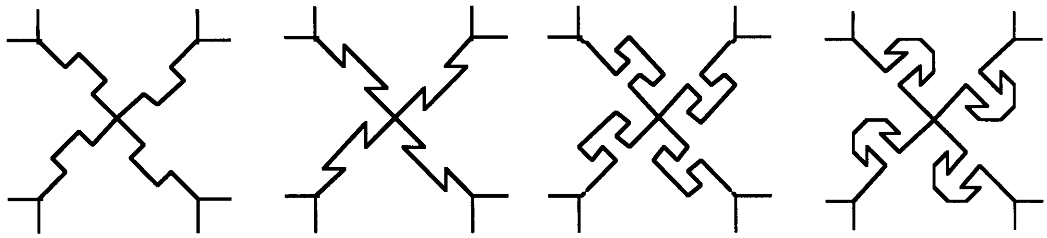


Fig. 5.43a Fig. 5.43b Fig. 5.43c Fig. 5.43d

Fig. 5.43: The four basic axisymmetric joints in the axisymmetric joint class: the axi-stud, axi-dovetail, axi-tee, and axi-barb joints. The basic four node types are easily applied to the axisymmetric joint layout.

Without a centerpiece, the joint region space is used more efficiently and effectively, as is detailed in analysis of Section 5.2.3. Also, in each joint configuration, there is a wider joint stance than that of the corresponding single node joint of the *N+1* joint class. That is, the moment distance of the axisymmetric joints is about three-quarters of the element thickness, as opposed to the one-half thickness joint stance of the single node joint designs.

5.2.2 Evolution of the AxiBarb™ Joint

Focusing on the axisymmetric barb joint of Fig. 5.43d, numerous design issues must be integrated into the detailed design to make the joint a feasible and more optimal joint. Fig. 5.44 shows the rudimentary axi-barb layout next to an modified and optimized AxiBarb™ joint.

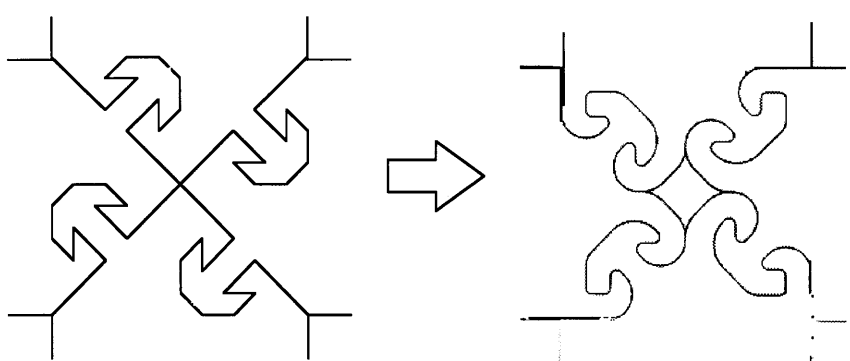


Fig. 5.44a Fig. 5.44b

Fig. 5.44a: The undeveloped axi-barb layout. Fig. 5.44b: The axisymmetric barb joint after engineering and manufacturing concerns are considered. Sharp corners and uneven thickness have been replaced with fillets and balanced design.

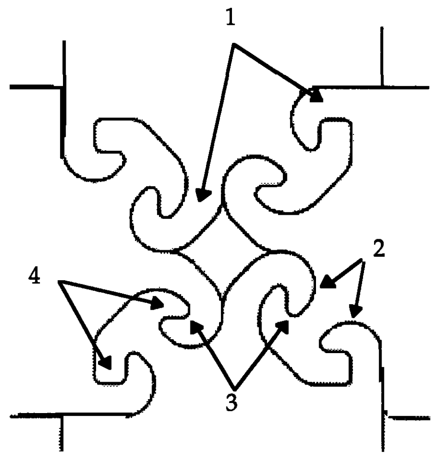


Fig. 5.45: Features of the AxiBarb™ joint design. Uniform wall thicknesses (1); large fillet radius at barb base (2); fillets on barb arms (3); square and corner barb ends (4).

The AxiBarb™ joint contains four major features that transform the basic axisymmetric barb joint layout into a viable joint, as shown in Fig. 5.45:

1. Uniform wall thicknesses: during extrusion, walls should be as uniform as possible to ensure even cooling and prevent voids and bulging.
2. Large fillets at barb base: The larger the radius, the lower the stress concentration.
3. Fillets at barb arm corners: prevents stress concentrators at critical points and sharp edges.
4. A square and a corner barb end on each barb head to prevent incorrect reverse assembly (square barb end cannot fit in corner barb-mate space).

It should also be noted that each of these features affects the dimensioning of the barb joint. For example, changing the fillet radii on the square and corner barb arms affects the thickness of the barb-mate arms. Thus, all four features must be simultaneously incorporated while also conforming to the basic axisymmetric joint layout.

Most of the joint features can also be parametrically described. For example, the wall thicknesses are one-tenth the overall thickness of the elements in this close-packed standard form. The fillet radius of the barb base is equal to the wall thickness. The fillet radii or the barb arms can be chosen as one-third the wall thickness. Other dimensions can be chosen following these key dimensions.

5.2.3 Finite Element Analysis of Joint Designs

The structural performance of joints and their contacting surfaces is an integral part of designing and evaluating structural products. In this study, designs from the patent-pending "Modular Storage System, Components, Accessories, and Applications to Structural Systems and Toy Construction Sets and the Like" are modeled and tested with finite element analysis. One of the applications and embodiments of the designs disclosed in the patent application is the formation of "cubby" arrays for modular storage structures. To evaluate the quality of an array's structure, a study of the joint is necessary. Also, comparison to existing or common joint designs is needed to validate the models.

Tension and Bending Models

A comparison of various joint designs has been conducted using finite element analysis. The analyses tested the joints in planar strain conditions and subjected the models to tension and bending loads as shown in Figs. 5.46 and 5.47.

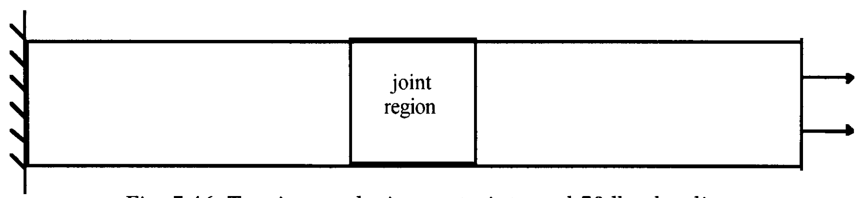


Fig. 5.46: Tension analysis constraints and 50 lbs. loading

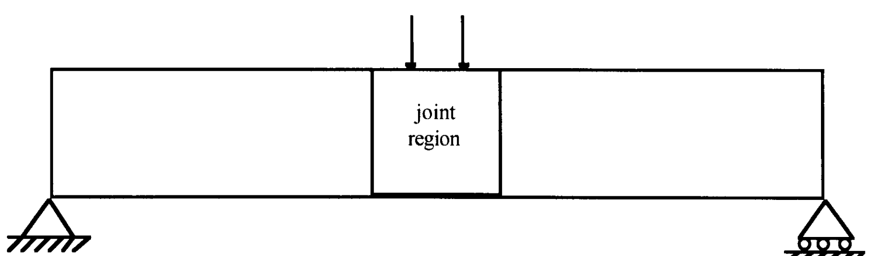


Fig. 5.47: Bending analysis constraints and 20 lbs. loading

Joint Configurations

Five joints have been modeled: single dovetail; single barb; axisymmetric dovetail; axisymmetric barb; a modified axisymmetric barb. These cross-sectional geometries are shown in Fig. 5.48 through Fig. 5.52.

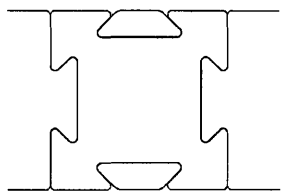


Fig. 5.48: Single dovetail

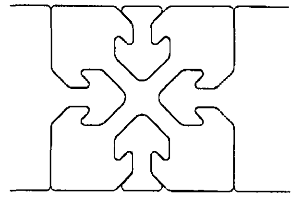


Fig. 5.49: Single barb

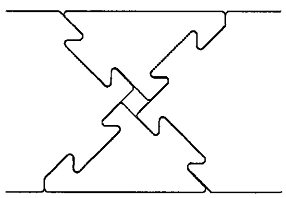


Fig. 5.50: Axisymmetric dovetail

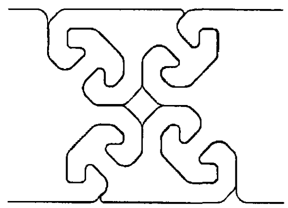


Fig. 5.51: Axisymmetric barb

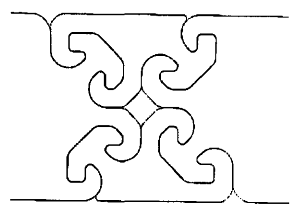


Fig. 5.52: Modified axi-barb

In each of the designs, the joints are formed by two beam elements and two "terminator" pieces. In the designs of Figs. 5.48 and 5.49, there is also a centerpiece as required by *N+1* class joints, while in Fig. 5.50 through Fig. 5.52, the axisymmetric designs preclude the need for a centerpiece. The terminator pieces have the same geometries as the beam elements but without the extension or beam length. All joint features fit within the one inch by one inch joint region to maximize comparability of results.

The joint models are one inch in height and six inches in total length, and are one inch in depth ("into the page"). Two thousandths of an inch (0.002") clearance are provided between all contact surfaces.

FEA Details

All analysis was conducted using Pro/MECHANICA 16.0 running on a DEC Alpha workstation. Finite element analysis settings included: mesh elements no greater than 3 in aspect ratio; multi-pass adaptive convergence method; 5% convergence based upon local displacement and local strain energy; maximum polynomial order of 9. The contact analysis assumed frictionless surfaces, a conservative assumption.

Material was assigned as polyvinyl chloride (PVC) with Young's modulus E=435100 psi and Poisson's ratio=0.4. Results are expressed in English units (inches, pounds).

Presented images are 9-level shading fringe patterns of principal stresses. Greyscale levels represent different stress magnitude ranges from image to image, so care should be taken when comparing graphical results. Some slight errors exist in modeling, an inherent feature of the analysis package's discretized meshing function; however, care has been taken to minimize these effects by minimizing the mesh size and aspect ratio.

Summary of FEA modeling

Tables T5.2 and T5.3 present the maximum stresses and maximum displacements of the four joint models. Note that while the values show significant differences, it is desirable to consider the locations and natures of these stresses to evaluate the joint designs. Detailed analysis of the FEA modeling are given in subsequent sections.

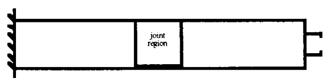
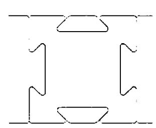
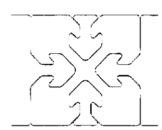
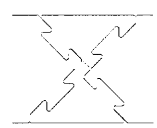
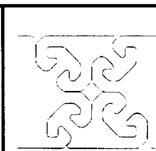
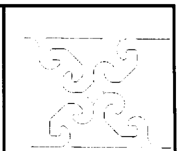
tension tests 50 lbs. load 	 dovetail	 barb	 axi-dovetail	 axi-barb	 modified axi-barb
max. stress (psi)	2713	1760	4594	2494	1600
max. displacement (in.) (at origin of applied load)	0.0092	0.0071	0.0110	0.0084	0.0074

Table 5.2: Results of tension analyses

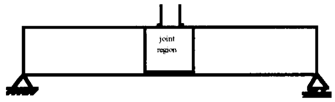
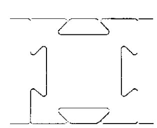
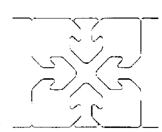
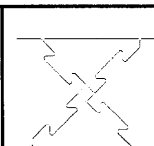
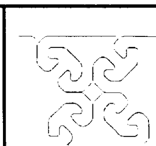
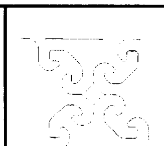
bending tests 20 lbs. load 	 dovetail	 barb	 axi-dovetail	 axi-barb	 modified axi-barb
max. stress (psi)	6376	6227	5105	4505	3246
max. displacement (in.)	0.083	0.093	0.040	0.040	0.036

Table 5.3: Results of bending analyses

The values in Tables T5.2 and T5.3 show that the fourth joint type, the axisymmetric barb joint, is stronger and stiffer than the most basic joint type, the single dovetail joint, in the tension and bending models. The following sections will similarly show that the axisymmetric barb designs of Figs. 5.51 and 5.52 are better overall joints than the single dovetail symmetry of Fig. 5.48. While the dovetail joint is commonly used in structural applications, it performs poorer than the axisymmetric barb.

Details of Joint Analyses

For each of the five joint designs, close-up views of the FEA stress fringe patterns are presented for the tension and bending models. Regions and locations of interest are noted and discussed.

Single Dovetail Joint

The single dovetail joint is considered the baseline of the modeling results. This dovetail is a commonly-used geometry, found in structural joining applications in wood, plastics and metals. In the test models, a 45° grip angle is used, with 0.024" and 0.026" radii fillets at acute-angled contact corners to lessen the effects of corner stress concentrations. The depth and breadth of the dovetail protrusion were subject to space constraints, such that four such protrusions would fit within the one square inch joint region within a section of the joint end or the centerpiece without creating a thin-walled region at any location.

The output FEA fringe image for the tension model is shown in Fig. 5.53.

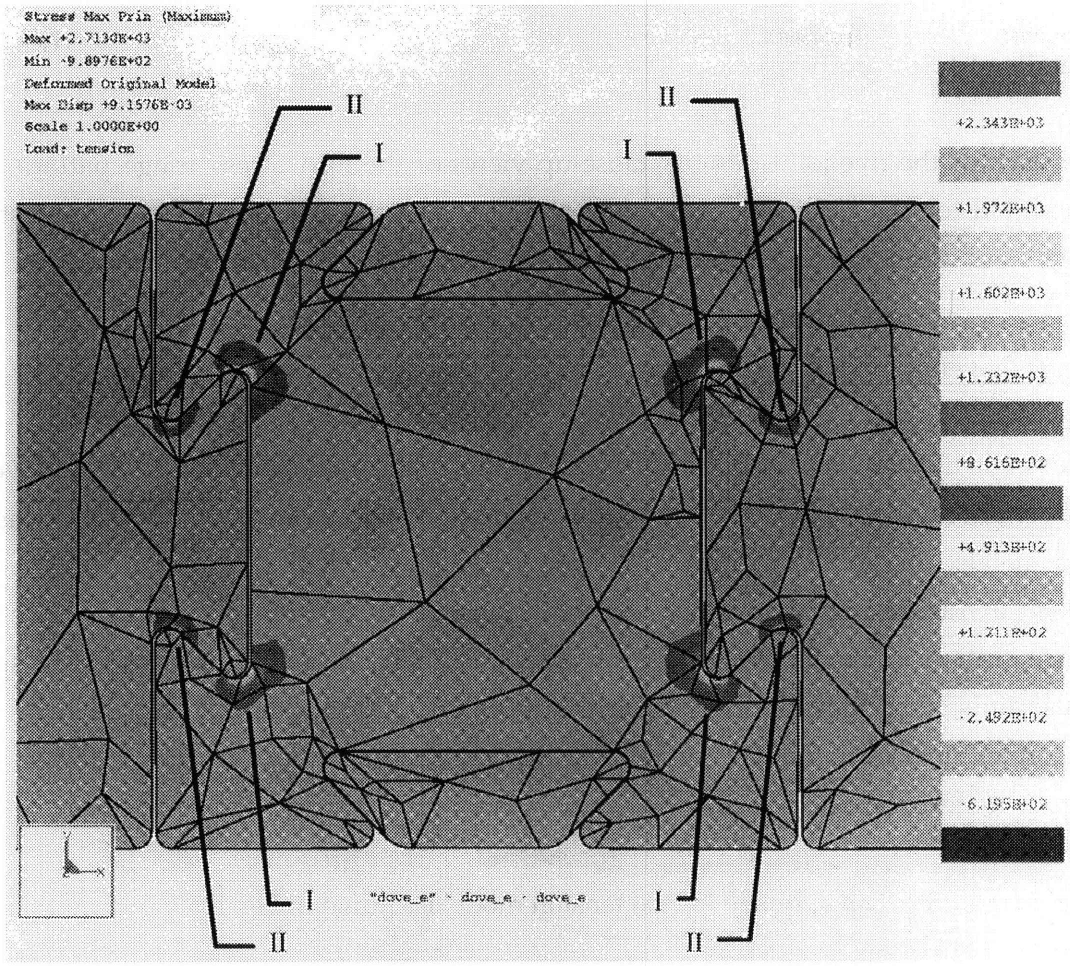


Fig. 5.53: FEA graph of tension model for dovetail joint

Locations labeled as "I" in Fig. 5.53 are regions of maximum stress, given as 2713 psi. Stress Regions II are slightly less than the maximum stress. Note that these regions occur at acute-angled corners.

In the bending model, the dovetail joint design produced the results shown in Fig. 5.54.

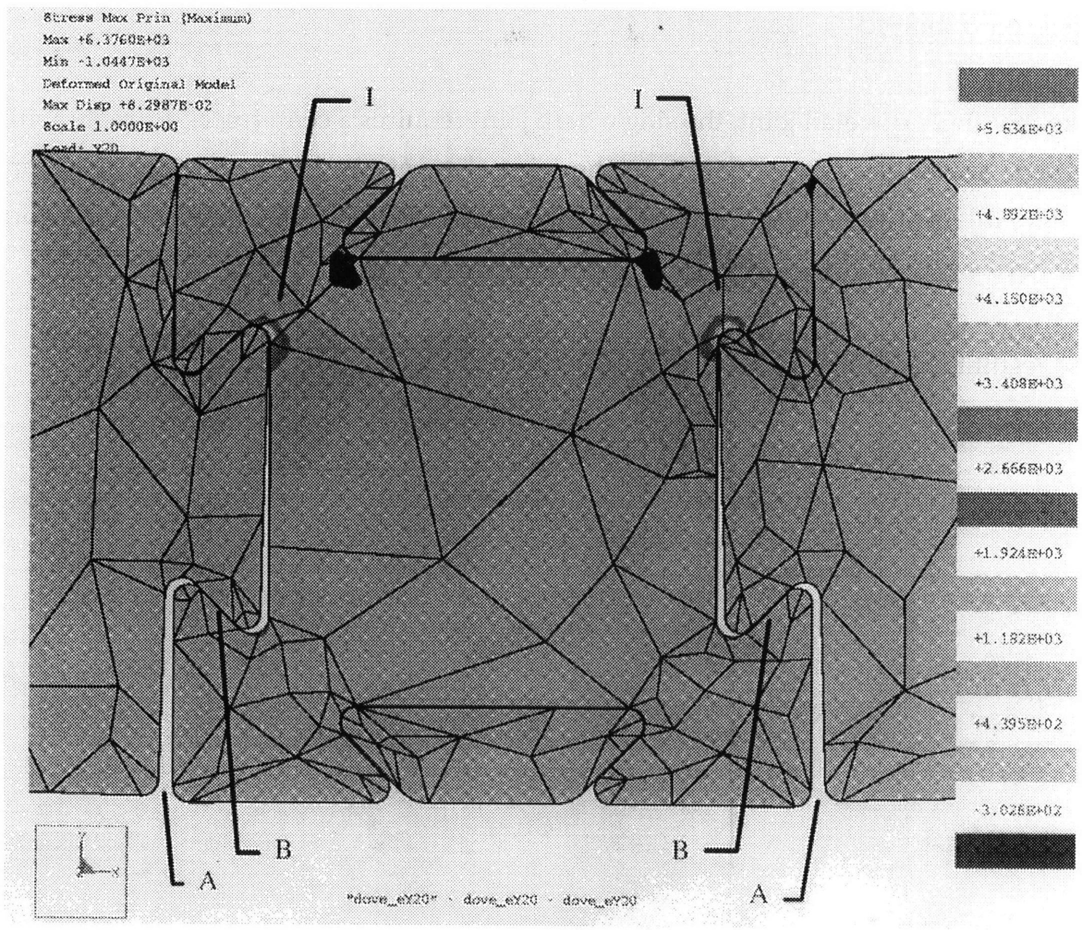


Fig. 5.54: FEA graph of bending model for dovetail joint

Maximum stresses are in Regions I, again at an acute angle on the centerpiece. Also, notice the significant spreading at Locations A. This spreading is a weakness of the dovetail design in applications where significant bending or non-tensile loads are present. Closer inspection reveals a root cause is due to the contact surfaces at Region B being nearly parallel to the direction of spreading induced by the load. This geometry, and thus the spreading effect at Region A, is an inherent disadvantage to the dovetail in the configuration of Fig. 5.48 as evidenced by the results shown in Fig. 5.54 above. The stress zones are also located near the top surface of the joint, equivalent to a short lever arm to counteract the load.

The dark regions near Regions I are compression bands of about 1000 psi, and are not considered detrimental to the joint strength or its performance.

Single Barb Joint

Like the single dovetail joint, the single barb joint requires a centerpiece to mate with the barbed, arrow-like projections from the joint elements and joint terminators. For this design, fillets of radii 0.019" and 0.021" are used for the acute-angled contact corners. The barb's grip angle is 135°.

The resulting graphical output from the tension model is shown in Fig. 5.55.

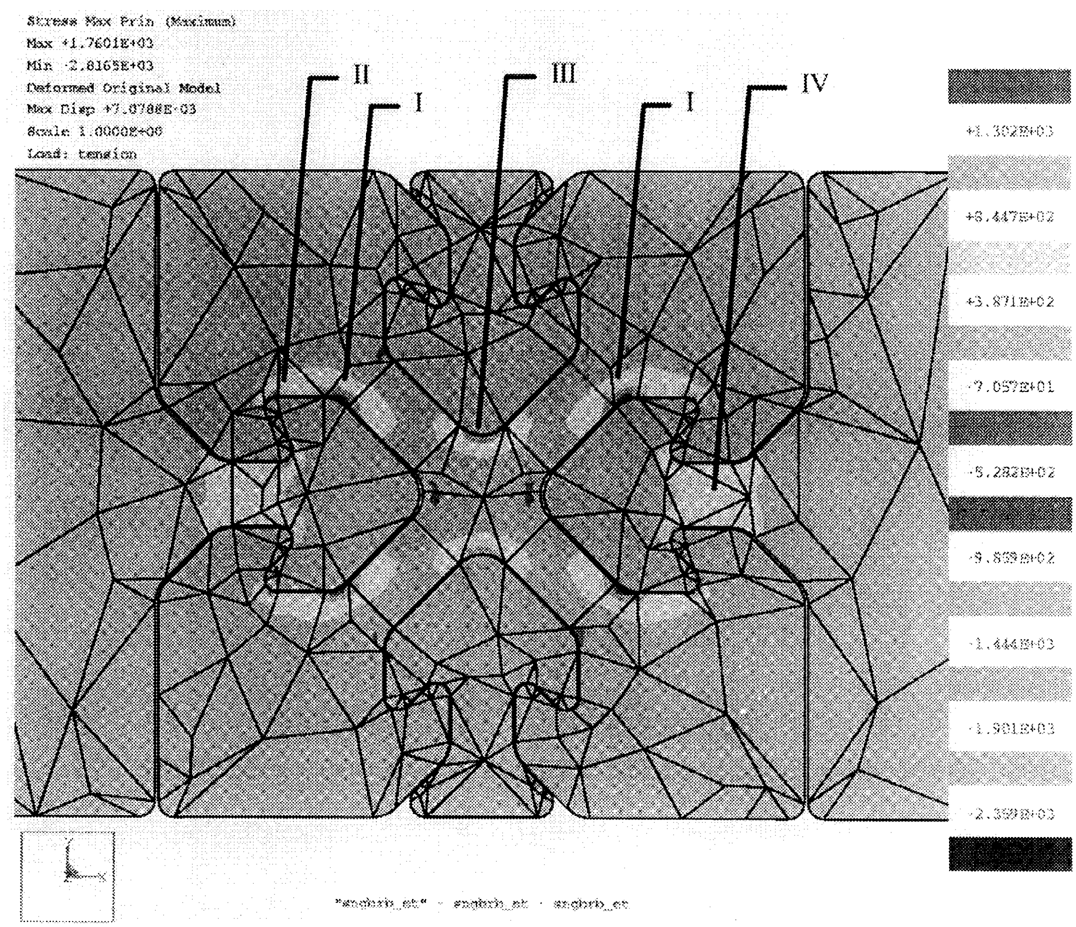


Fig. 5.55: Single barb joint in tension model

Maximum stresses for the single barb design for this tension model were given as 1760 psi, occurring at Stress Regions I and II. Lower but sizable stresses occurred at Regions III and IV. Note that the entire "necks" of the barbs at Regions IV are in tension.

The results for the single barb joint in the bending case is shown in Fig. 5.56.

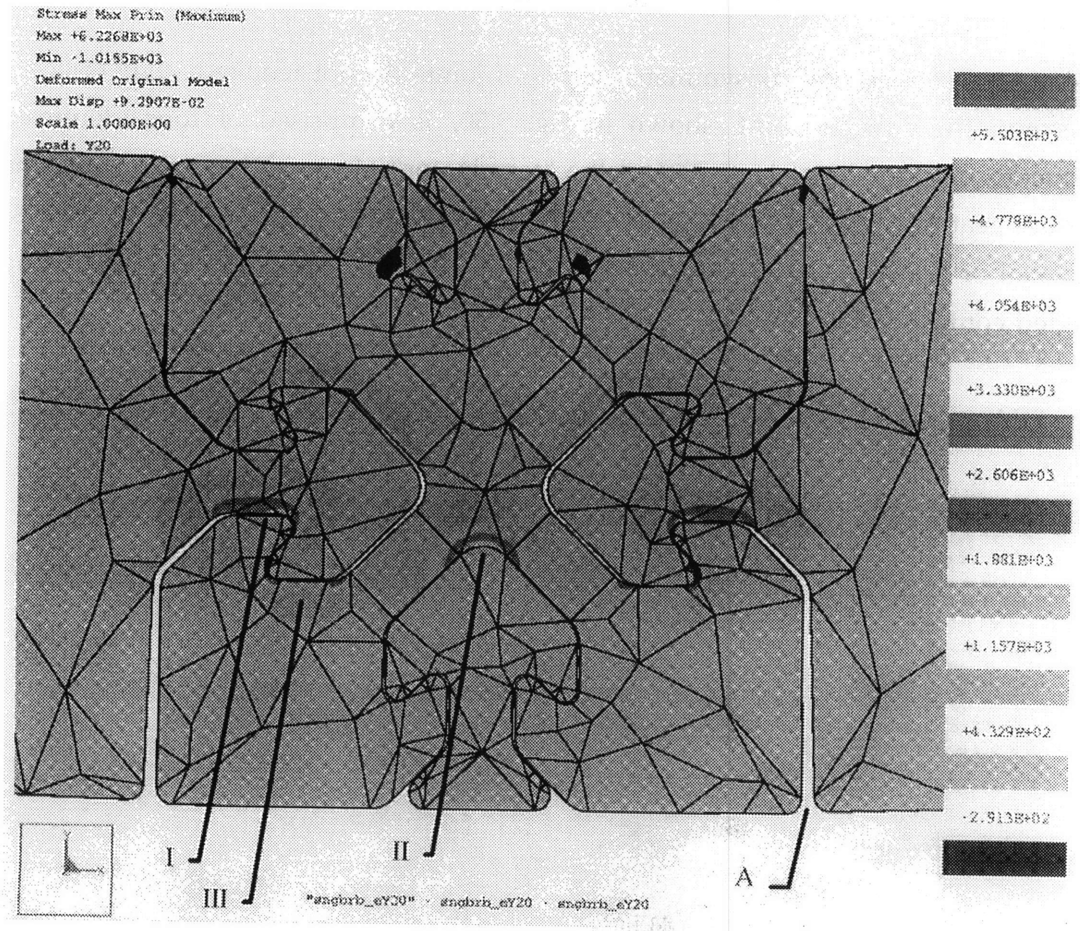


Fig. 5.56: Single barb joint in bending model

Stress Regions I features highest stress of 6227 psi at the acute angle of the centerpiece. Similarly high stresses occur on the centerpiece at Regions II and III. In the bending model, the single barb joint suffered the same spreading at Location A, as did the single dovetail joint shown in Fig. 5.54.

However, the location of maximum stresses are halfway down the joint thickness (in the Y dimension); hence the longer effective lever arm compared to the single dovetail in Fig. 5.48 would imply a lower maximum stress. However, the thin barb neck negates this advantage. An improvement to this joint design would be to thicken the barb neck, thereby reducing the maximum stresses in both the tension model and the bending model.

Axisymmetric Dovetail Joint

Using a novel geometry, axisymmetric types of joints do not require a centerpiece. The axisymmetric dovetail joint, shown in Fig. 5.50, is comprised of four identical end elements; both the long elements and the "terminator" elements have the same mating surface features, and are as equally interchangeable in its joint system as the single dovetail or the single barb designs are in theirs. For this model, fillet radii for acute-angled contact corners are 0.019" and 0.021".

The FEA graphical results for the tension model is shown in Fig. 5.57.

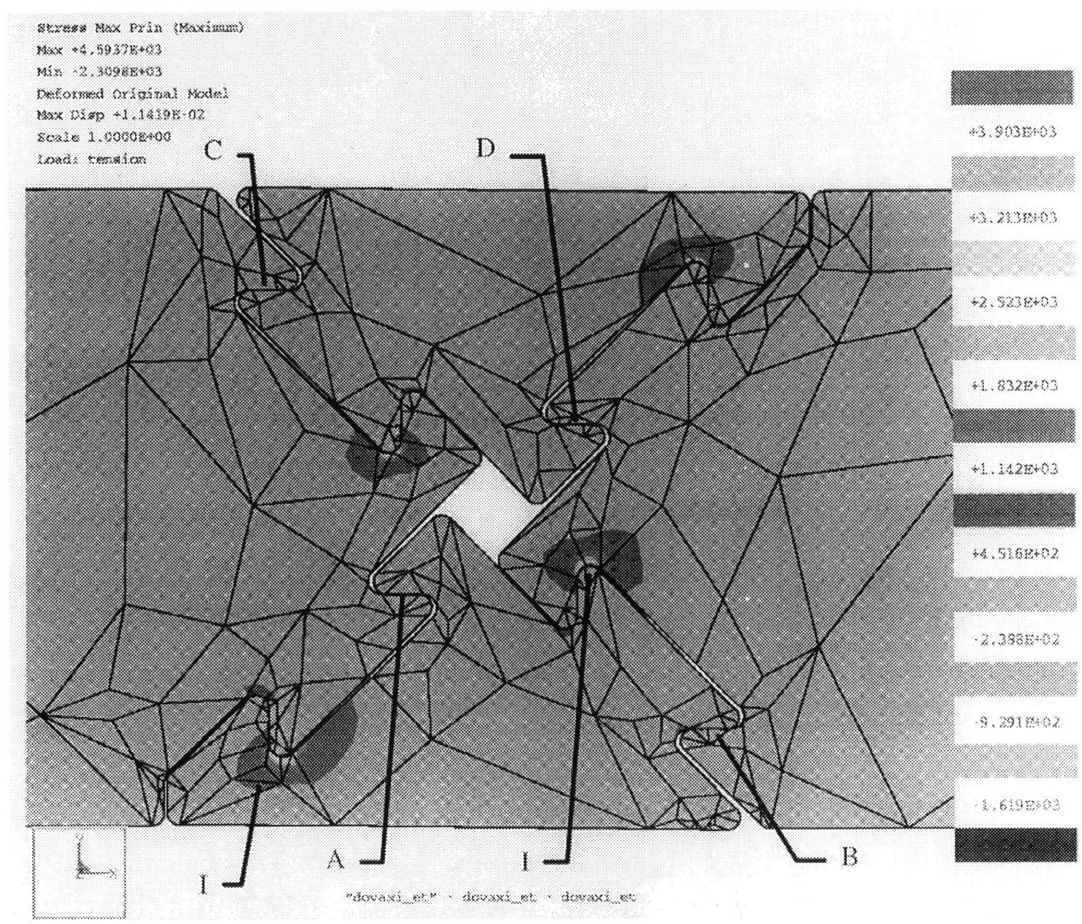


Fig. 5.57: Tension model for axisymmetric dovetail joint

The maximum stress of the tension model is 4594 psi, twice as high as the single dovetail joint model. This stress occurs at the locations at Regions I. The likely reason for such high stresses is due to the non-contacting surfaces between elements at Locations A, B, C and D. In these areas, the mating surfaces are exactly parallel to the direction of the applied loading; hence the axisymmetry of the dovetail in this joint design performs poorly under tensile loads. Therefore, the entire load is distributed through a minimal number of contact areas at Regions I, where the wall thickness of the elements are at a minimum.

For the bending model, with the 20 lbs. loading in the -Y direction, the results are shown in Fig. 5.58.

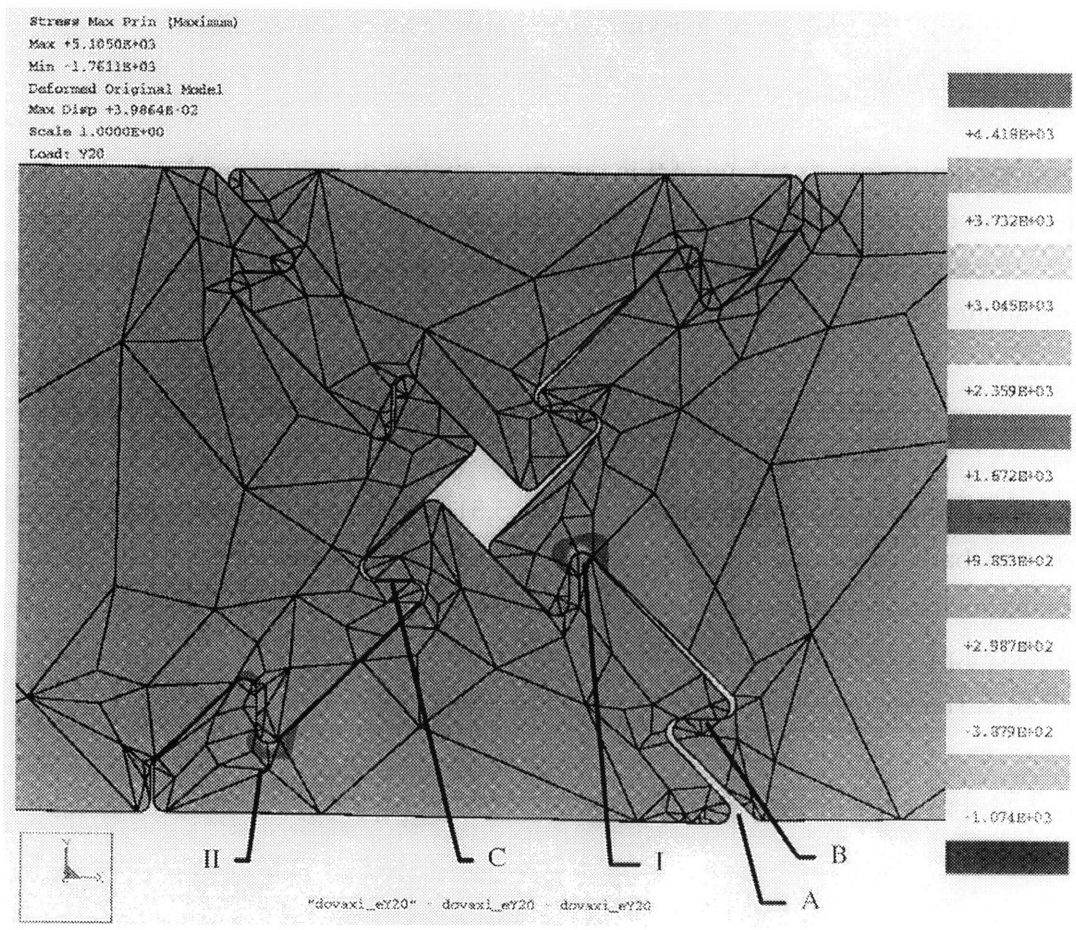


Fig. 5.58: Axisymmetric dovetail joint in bending model

The finite element analysis shows this axisymmetric dovetail joint to be more effective at supporting the -Y load than the single dovetail or the single barb joints. The maximum stress is around 5100 psi, located at Region I in Fig. 5.58. This area of stress concentration is located at the thinnest wall section of the joint element. The area of second-highest stresses occurs at Region II. Regions I and II in Fig. 5.58 are the same locations as the high stress locations in the tension model of Fig. 5.57.

The gap at Location A is significantly smaller than the gaps in the single dovetail or single barb joints of Figs. 5.54 and 5.56, respectively, and the maximum displacement of the joint is less than half of those of the single dovetail and single barb cases. Fundamentally, however, the slipping surfaces at Locations B and C contribute little to the load-capacity. Thus, the load-capacity could be increased and maximum displacement could be decreased by improving contact at Locations B and C. In order to do so, the grip angle of the dovetail would have to be increased above the present 45°. This supports the design of axisymmetric barbs, where the barbs have a grip angle greater than 90°.

Another significant advantage of this design is smaller deflection in -Y loading; it has a maximum displacement of around 0.040", as compared to the single dovetail and single barb joints under the same loads. Thus, this axisymmetric joint is stiffer than the previously displayed joints.

Axisymmetric Barb Joint

The axisymmetric barb joint design of Fig. 5.51 comprises of axially-symmetric and repeated barb geometry. Each joint element features a barb and a barb mate. For reasons such as design-for-assembly, the barb head itself it not symmetric – one arm is a rounded square while the other features a more acute corner. The acute corners of mating surfaces are filleted at radii 0.024" and 0.026".

Fig. 5.59 shows the results of the FEA tension model for the axisymmetric barb joint.

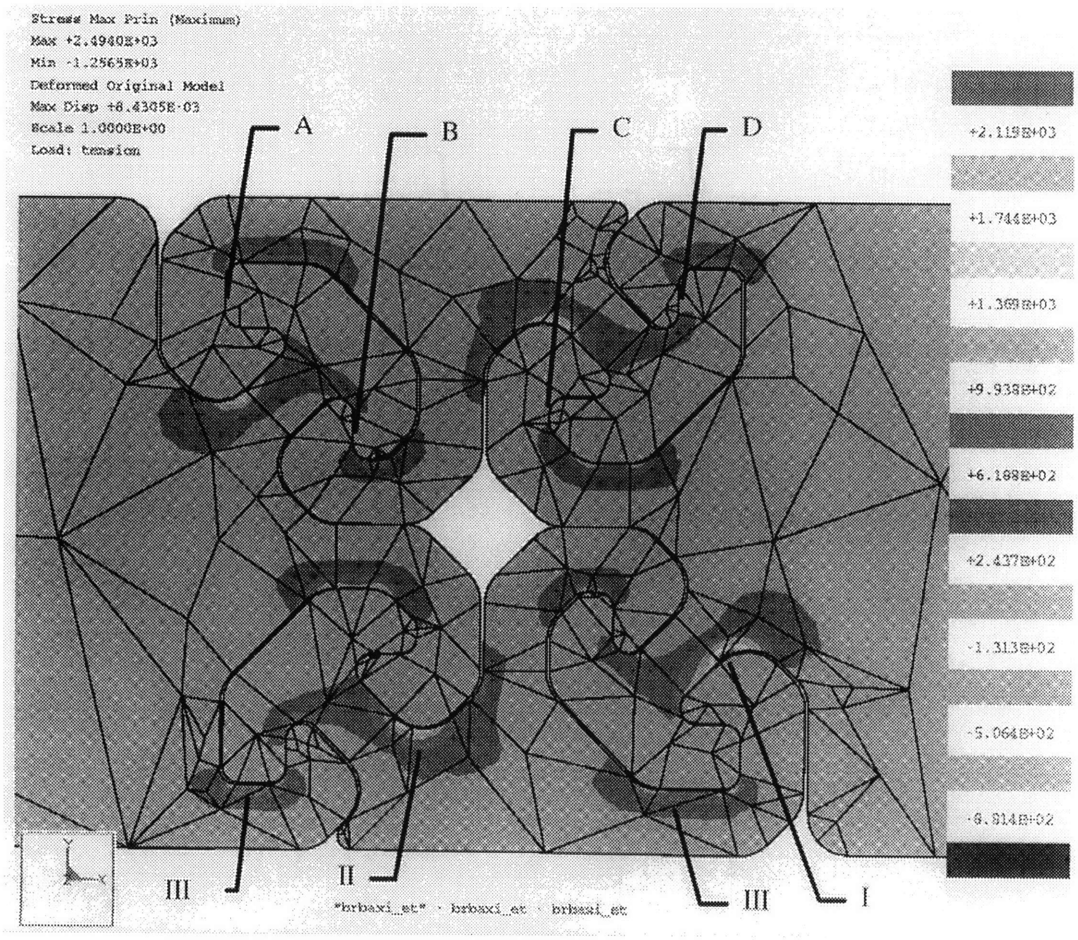


Fig. 5.59: Axisymmetric barb joint in tension model

The maximum stress in the tension model is 2494 psi, located at Region I in Fig. 5.59. This stress value is about 8% less than that of the single dovetail design of Fig. 5.48 and modeled as in Fig. 5.53. Secondary stress regions are at Regions II and to a lesser extent at Regions III.

The stresses are distributed throughout 12 large regions in the entire joint assembly, as opposed to 8 more-concentrated stress regions in all the other modeled joints. This even distribution of load is due to good surface contact at Locations A, B, C and D, where mating surfaces contact orthogonally to the direction of tensile loading. The distribution also shows that the wall thickness of the barb arms and mating arms are appropriate, and that optimization of the geometry may yield only minor improvements for tensile loading cases.

The FEA results of the axisymmetric barb joint in bending is shown in Fig. 5.60.

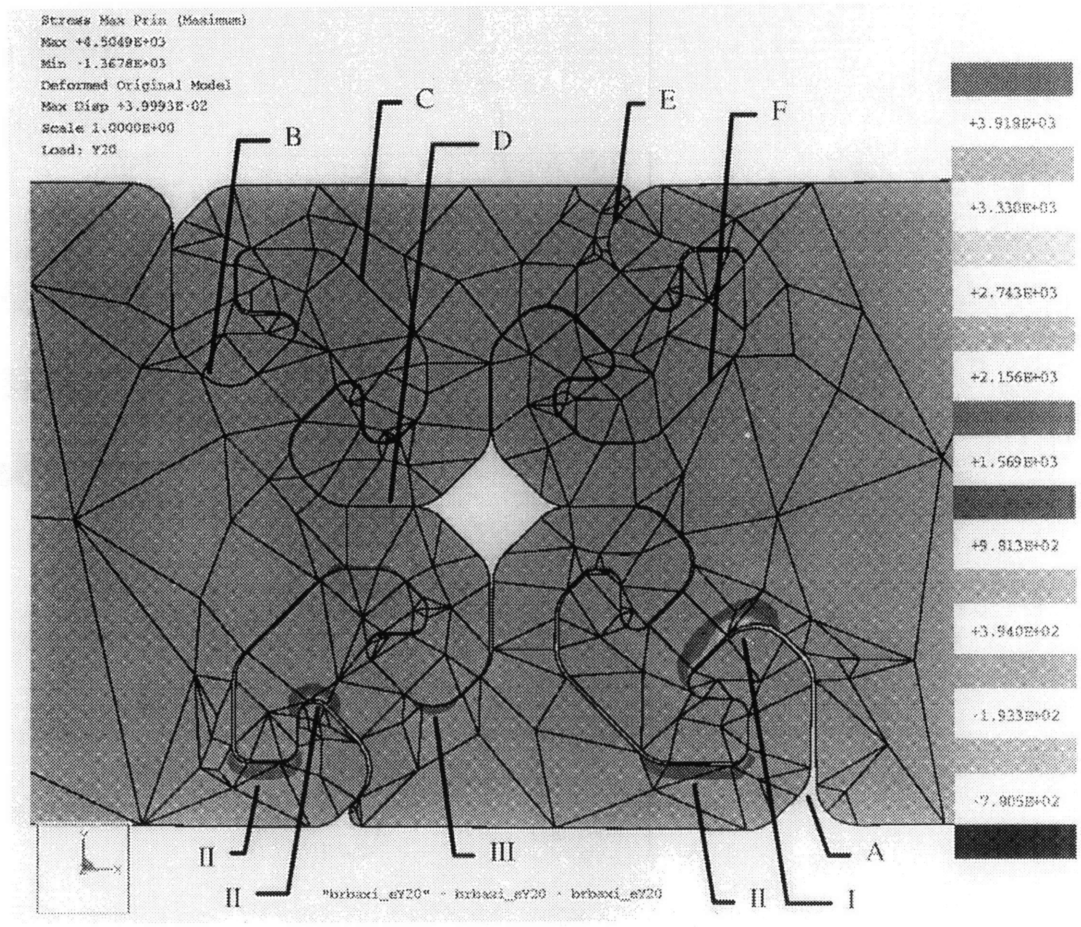


Fig. 5.60: Bending model for axisymmetric barb joint

The maximum stress of the axisymmetric barb joint in the bending model is 4505 psi, the lowest of the four joint designs analyzed. This stress occurs at Region I, with lower stresses at Regions II and III of Fig. 5.60. *The maximum stress magnitude of the axisymmetric barb joint is about 30% lower than that of the single dovetail joint in the bending model.*

The axisymmetric barb joint performs well in the -Y loading model partly due to a greater effective lever arm to counteract the load, consequently reducing the stresses on the protruding barb neck at Region I. The location of Region I in Fig. 5.60 is two-thirds of the way down from the top surface whereas the single dovetail Region I in Fig. 5.54, for comparison, makes its significant contact only one-quarter of the overall joint height from the top surface.

Also, the top element of the axisymmetric barb makes contact with mating elements at several locations along its surface, at Locations B, C, D, E and F, for example. This tight fit lends support and stiffness and does not exist with the other joint types shown in Figs. 5.54, 5.56 and 5.58. As a result, the gap at Location A is less than that of the single dovetail and single barb designs and is similar to the axisymmetric dovetail joint design. Similarly, the maximum displacement of the axisymmetric barb joint is 0.040", equal to that of the axisymmetric dovetail joint and less than half the maximum displacement of the single dovetail and single barb joints, resulting in a stiffer joint.

Modified Axisymmetric Barb Joint

The finite element analysis for the original axisymmetric barb joint displays superior structural properties over the other examined joint configurations. By noting the highest stresses in the joint system occur at the trunk of the barb necks in both the tension and bending models, seen at Regions I in Figs. 5.59 and 5.60, the original axisymmetric barb joint is consequently modified to improve performance. The change in the barb neck geometry is shown in Fig. 5.61.

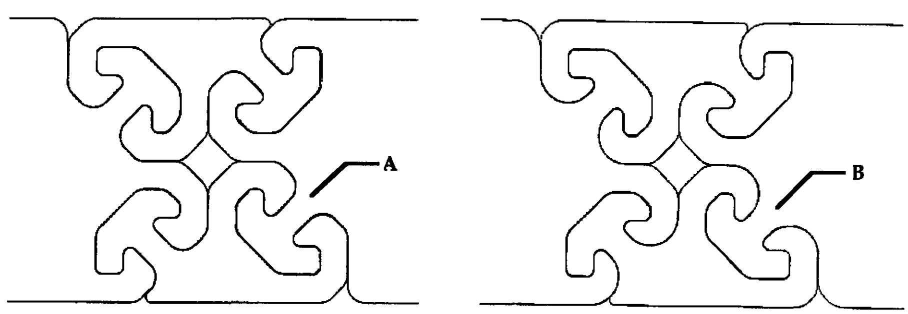


Fig. 5.61a Fig. 5.61b

Fig. 5.61a: Original axisymmetric barb joint; Fig. 5.61b: Modified axisymmetric barb joint. Note the changes in barb neck geometry.

The original design, in Fig. 5.61a, shows the uniform width of a barb neck at A. The modified barb joint, in Fig. 5.61b, has a tapered barb neck at B, with the barb trunks blending into the body of each joint element. This change is intended to minimize the stress concentration at the barb neck. As confirmation, the tension and bending FEA models were executed and are shown in the next figures.

Fig. 5.62 displays the FEA results for the modified axisymmetric barb joint in the tension model. For this joint, there are several locations, labeled Regions I, each having near the maximum stress. For this model, the maximum stress is only 1600 psi.

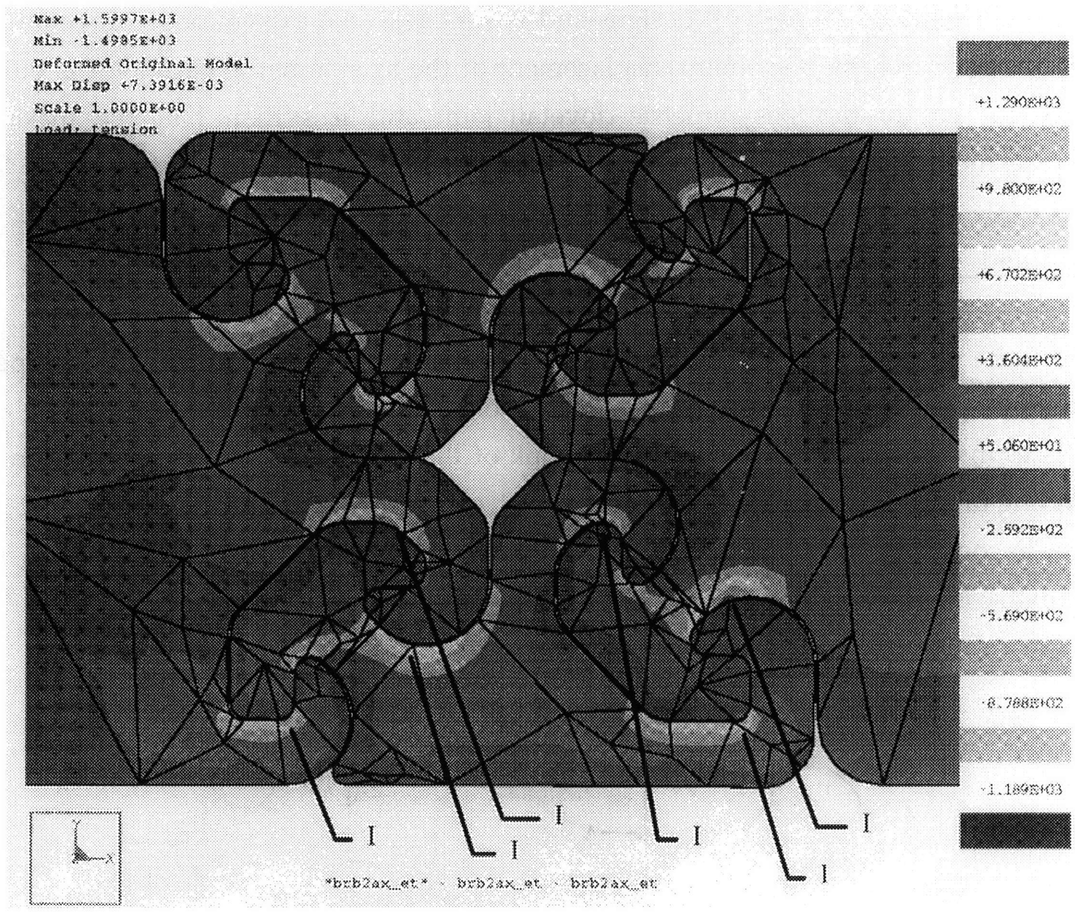


Fig. 5.62: Modified axisymmetric barb joint in tension model

Comparing the FEA tension model results for this modified joint in Fig. 5.62 to the original axisymmetric barb joint in Fig. 5.59, it can be discerned that while the tensile stresses in the joint systems occur at the same general locations, the magnitude of those stresses are more equal to one another in the modified joint. Hence, the strategy of iterative design and analysis can lead to an improved design.

The modified axisymmetric barb joint in the bending model is shown in Fig. 5.63.

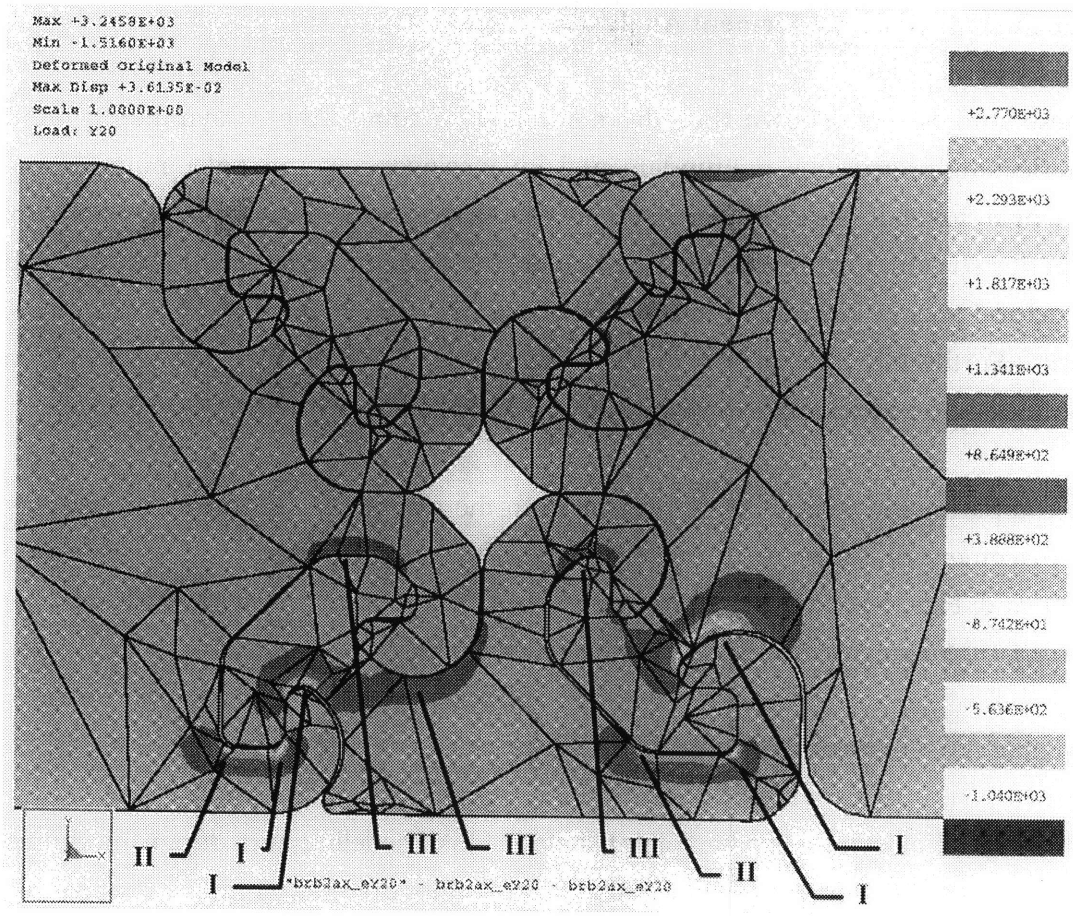


Fig. 5.63: Bending model results for the modified axisymmetric barb joint

Fig. 5.63 shows that there are three locations, labeled Regions I, that exhibit at or near the maximum stress of 3246 psi. Also, there are other stress regions of significant denoted as Regions II and III. It may be seen from comparing these bending results of the modified design with those of Fig. 5.60 for the original barb design that the new design distributes the applied load throughout the joint more effectively.

Further optimization of the axisymmetric barb joint design is feasible. In particular, changes to the fillet radii to lower stresses in Regions I and II may further distribute the applied load to Regions III.

Another effect of the modifications to the barb geometry is that the maximum displacement of the joint has decreased, and that the spreading between joint elements is less than in other joint models.

Conclusions of Finite Element Analyses

These studies have shown that the new class of joints, the axisymmetric family of interlocking protrusions, is a fundamental advance over conventional joining means such as single dovetail joint. The analysis reveals that axisymmetric joints generally exhibit superior structural properties. In particular, the axisymmetric barb joints show better structural properties in both tension and bending loads than all of the other modeled joints. Furthermore, the axial symmetry allows for tiled structures, systems that can be continually repeated and expanded with the same joint element.

By comparing the results of the FEA, in both the magnitudes of maximum stresses and displacement of Tables T5.2 and T5.3, and in the stress patterns shown in Figs. 5.53-5.60 and Figs. 5.62 and 5.63, it can be seen that *the axisymmetric barb joint designs outperform the single dovetail joint in strength and stiffness.*

<u>Original Axisymmetric Barb Joint</u>

The original axisymmetric barb joint, before FEA modeling and design modifications, demonstrates better performance than the single dovetail joint. The results are summarized as:

- The axisymmetric barb joint outperforms the single dovetail joint in *tension* tests:
    - 8% lower maximum stress
    - 8% less deflection

- The axisymmetric barb joint outperforms the single dovetail joint in *bending* tests:
    - 29% lower maximum stress
    - 52% less deflection

<u>Modified Axisymmetric Barb Joint</u>

Changes to the original axisymmetric barb joint improved performance by 36% and 28% in the maximum stress over the original design in tension and bending models, respectively. *Compared to the single dovetail joint, the modified axisymmetric barb joint demonstrates even greater structural performance.*

- The modified axisymmetric barb joint outperforms the single dovetail joint in *tension* tests:
    - 41% lower maximum stress
    - 19% less deflection
- The modified axisymmetric barb joint outperforms the single dovetail joint in *bending* tests:
    - 49% lower maximum stress
    - 56% less deflection

Varying the modeling conditions, such as clearances and load values, result in different values for the tension and bending stresses and displacements. Also, design changes may be made to the other joint geometries to improve their modeled performance slightly. However, the results nonetheless show quantitatively and qualitatively that the axisymmetric barb joint design is superior over the single dovetail joint design.

5.2.4 Panel Design

As mentioned in Section 5.1.3, the design of the panels and the integrated truss must consider thickness and width concerns as well as fractional panel and plug-in geometries. In order to accommodate various objects efficiently, without wasted space or excessive panel deflection, these panel dimensions must be chosen carefully.

Fig. 5.64 shows a nested cubby structure using one-quarter, one-half, three-quarter and full-width panels.

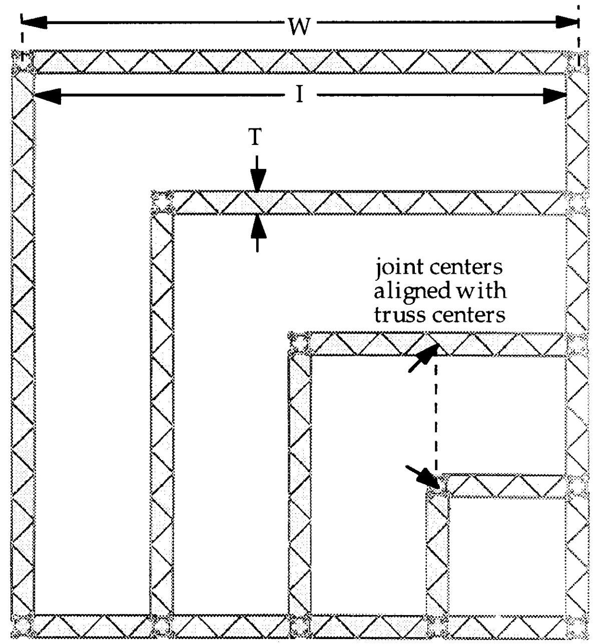


Fig. 5.64: Fractional panels require consistent design of the truss structure to ensure symmetries.

For the full panel width cubby, center-to-center distance between joints is *W*. The overall thickness of the panel is T; hence, when using an approximate truss of maximum offset (so that $L = T$), the center-to-center joint distance *W* of the full width panel is equal to:

$$W = (th)\ T \qquad (E5.8)$$

where *(th)* is the number of trussholes, observing the minimum fractional panel width condition (must have even number of trussholes). At the end of the panel, the trusshole will not be complete because of the joint end features, as shown in Fig. 5.65:

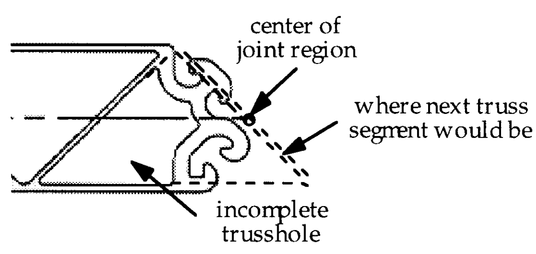


Fig. 5.65: Joint features and the incomplete trusshole. The joint center lies at the center of a virtual truss segment to maintain symmetry of fractional panels.

Since the joint center lies at the center of where the next truss segment would be located, the symmetry of the trusses and trussholes is maintained. As in Fig. 5.64, the fractional panel's joint centers lie aligned with the centers of truss segments in other fractonally-sized panels.

The actual space inside the cubby, not including the panel thickness itself, is the internal space *I*:

$$I = W - T = (th)\ T - T = (th - 1)\ T \qquad (E5.9)$$

As *(th)* must be a multiple of an even number (of the smallest fractional panel), and since panel width is also tied to panel thickness, careful selection of fractional scheme and panel dimensions is critical to satifying the storage system applications.

For example, Fig. 5.64 shows a quarters fractional scheme, with the one-quarter panel having 6 trussholes. Thus, the full-width panel has 24 trussholes. Using a maximum offset approximate truss, center-to-center distance between trussholes is *L*, equal to the panel thickness *T*, from Eqn. E5.3a. The internal space *I* is equal to $(24 - 1)\ T$, or $23\ T$, from Eqn. E5.9. Similarly, the sizes of the other fractional panels follow, shown in Table T5.4, and with an example thickness of $T = 1.00''$:

fractional size	panel width *W*	*W* (with *T=1.00″*)	internal space *I*	*I* (with *T=1.00″*)
full width	*24 T*	24.0″	*24 T - T= 23 T*	23.0″
three-quarters	*18 T*	18.0″	*18 T - T = 17T*	17.0″
one-half	*12 T*	12.0″	*12 T - T = 11T*	11.0″
one-quarter	*6 T*	6.00″	*6 T - T = 5T*	5.00″

Table T5.4: A sample set of quarters-scheme fractional panels. Panel thickness is given as 1.00″.

Conversely, when designing for desired internal space *I*, the resulting panel thickness *T* is equal to:

$$T = \frac{I}{(th - 1)} \qquad (E5.10)$$

Given all of these relations, a Cubbeez™ system may be designed. The following constraints or conditions must be given:

- Desired internal space for objects to be stored
- Fractional panel scheme (thirds, quarters, etc.)
- Maximum and minimum acceptable panel thicknesses
- Number of trussholes for smallest fractional panel

It is recommended that the selection of panel dimensions be calculated with a spreadsheet so that the panel parameters affecting all fractional panels can be changed easily.

Example: Panels for storage bins and A4 binders

A typical organization structure would hold both storage containers and items such as papers and binders. The common storage container, as made by such companies including Rubbermaid, measures about 16" in width. Access space makes the required internal cubby dimension on the order of 18". A4 binders require at least 13" of internal space. This includes the height of the binder itself (approximately 12") plus access space for fingers. Thus, there are two design objectives: cubbies must provide approximately 18" and 13" of internal space.

While one could merely design for one large panel with 18"on internal space, the storage of binders in that cubby would be inefficient, with much wasted space. Hence, a fractional panel scheme is desired. For this case, a thirds scheme and a quarters scheme are considered.

According to Egn. E5.10, the panel thickness T is related to the number of trussholes. For a thirds fractional scheme, the smallest panel, a one-third panel, must have an even number of trussholes, so the full-width panel must have a trusshole count divisible by 2 *and* 3, or a multiple of 6. Thus, 18, 24 and 30 are valid trusshole counts for a full-width panel in a thirds fractional scheme. For the quarters fractional scheme, the one-quarter panel must have an even number of trussholes, so the full-width panel must have a trusshole count divisible by 8. Therefore, 16, 24, and 32 are valid trusshole counts for a full-width panel in a quarters fractional scheme. Notice that 24 trussholes is valid for both schemes.

By Eqn. E5.10, panel thickness is related to trusshole count and panel width. For a full panel providing exactly 18" of internal space using 24 trussholes, the panel width W equals:

$$T = \frac{I}{(th-1)} = \frac{18"}{(24-1)} = 0.7826" = 19.88mm \qquad (E5.11)$$

Center-to-center panel width simply equals 24 T = 18.7826″ = 477mm. This panel accommodates the storage container easily.

Now the fractional panels must be checked to accommodate the 13″ internal space for the A4 binders. For the thirds fractional scheme, the following table of dimensions results, using the 18″ internal space provided by the full panel with 24 trussholes:

fractional size	number of trussholes	panel width	internal space
full width	24	18.78″	**18.00″**
two-thirds	16	12.52″	11.73″
one-third	8	6.261″	5.478″

(panel width = 0.7826″ = 19.88mm)

Table T5.5: A set of thirds-scheme fractional panels for storage bins. The full width panel would accommodate a 16″ storage container, but a two-thirds paneled cubby is too small for binders.

The internal space of the panel smaller than the full width is less than 13″ needed for an A4 binder. In order to increase that internal space to 13″, the panels must be larger, and consequently thicker, resulting in the set shown in Table T5.6:

fractional size	number of trussholes	panel width	internal space
full width	24	20.80″	19.93″
two-thirds	16	13.87″	**13.00″**
one-third	8	6.933″	6.067″

(panel width = 0.8666″ = 22.01mm)

Table T5.6: A set of thirds-scheme fractional panels for storage bins and A4 binders. While the two-thirds paneled cubby would hold the binders, the full-width paneled cubby would be too large for the containters.

While this set is a viable option, the full width panel may be too large and waste space. Also, since the deflection of a panel is proportional to the square of the width, the full panel of Table T5.6 will deflect about 20% more compared to the panel in Table T5.5.

Now consider a quarters fractional scheme. Again using a full panel width of 24 trussholes to accommodate an 18″ internal space, the following set of panels results, shown in Table T5.7:

fractional size	number of trussholes	panel width	internal space
full width	24	18.78″	**18.00″**
three-quarters	18	14.09″	**13.30″**
one-half	12	9.391:	8.609″
one-quarter	6	4.696″	3.913″

(panel width = 0.7826″ = 19.87mm)

Table T5.7: A set of quarters-scheme fractional panels for storage bins and A4 binders. The full-width and the three-quarters panels accommodate the objects with little wasted space.

In this case, both the storage container and the A4 binders are well-accommodated by the full and three-quarters paneled cubbies.

Another iteration of this design can take into account standard sizes in industry. As the panel thickness of the set in Table T5.7 is 19.87mm, it will almost be accommodated by panel fittings and tapes for 20mm thick paneling. Increasing the panel thickness to 20.00mm, or 0.7874″, results in the panel dimensions of Table T5.8:

fractional size	number of trussholes	panel width	internal space
full width	24	18.90″ = 480.0mm	**18.11″ = 460.0mm**
three-quarters	18	14.17″ = 360.0mm	**13.39″ = 340.0mm**
one-half	12	9.448 = 240.0mm	8.661″ = 220.0mm
one-quarter	6	4.724″ = 120.0mm	3.937″ = 100.0mm

(panel width = 0.7874″ = 20.00mm)

Table T5.8: A set of quarters-scheme fractional panels conforming to English units. With a panel thickness of 20.00mm, the panel widths and internals spaces are even multiples of 10mm.

The detailed design of the panels are also dependent upon manufacturing and material issues, as well as marketing and cost factors. These areas must be considered and tested before full production of the product commences.

5.2.5 Manufacturing and Material Issues

One of the decisions to be made in producing Cubbeez™ panels is the material used in extrusion. Two materials initially have potential: aluminum and plastics.

Aluminum has a modulus of 10 Mpsi and a tensile strength on the order of 40 kpsi. For a panel 10″ deep, and a nominal barb neck thickness of 0.050″, the maximum tensile load can be 20,000 pounds. However, one of the limitations of extruded aluminum is that for multi-cavity cross-sections with a large aspect ratio and large circumferential extrusion size, a wall thickness of 0.050" is an order of magnitude too thin to be achieved with today's extrusion processes. Hence, manufacturing limitations alone preclude aluminum from being a viable material.

Plastics, on the other hand, are commonly extruded in large aspect ratios with multiple cavities. Vinyl, or polyvinyl chloride (PVC), is used in thinwall extrusions for home outdoor siding paneling. Thinwalls are on the order of 0.030" and 0.050" in thickness with only a few mils surface irregularity. Polycarbonate is another plastic extruded in multi-cavity paneling, used as greenhouse panels, for example, and can be extruded down to wall thicknesses on the order of 0.010" thick. Polystyrene (PS) is a lighter plastic with low cost. Other plastics that can be extruded are polyolefins such as polypropylene and thermoplastic polyesthers such as polyethylene terephthalate (PET).

Polycarbonate is a good candidate due to its current manufacturability and favorable structural properties. Its flexural modulus is minimally 300 kpsi and its tensile strength is on the order of 10 kpsi and can be increased with fiberglass reinforcement. However, the main drawback is the cost of polycarbonate. Similar multi-cavity extruded panels can sell at $5 per square foot. As will be described later, this price may be too high to be viable for an intended low-cost storage application.

Rigid PVC, on the other hand, is more affordable while exhibiting satisfactory material properties. It has a tensile strength on the order of 6 kpsi, and tensile modulus of at least 300 kpsi, and good chemical resistance, a property some lighter and cheaper plastics do not have. PVC, like polycarbonate, is currently extruded in cross-sectional forms quite similar to the cubby panel designs. Talc can also be added to PVC resin mixtures, increasing its modulus, lowering its overall cost, and lowering surface friction during extrusion and in product assembly, as talc is an excellent dry lubricant. PVC can also be extruded with a partial regrind content, saving on virgin resin usage and thus overall cost. A drawback of PVC is its environmentally unfriendly characteristics, a growing concern in today's industry.

Polystyrene has a lower modulus, from 100 kpsi, and a lower tensile strength, from 2 kpsi, than PVC. PS also has poorer resistance to chemicals. It can also be fiberglass reinforced, and is a common plastic in extrusions.

5.2.6 Cost Estimates and Effects on Design

For a low-cost storage system, the price of the system must be competitve with existing alternatives. Comparing to existing, non-modular storage systems, a \$100 sales price for a 2x3 array structure, with 1.5ft. square cubbies and 2ft. depth, can be established. Build-it-yourself plans cite a cost at \$14 per cubby for materials alone. These systems are typically made of unfinished pine boards, or with medium-density fiberboard coated with melamine. Construction, fabrication and assembly are often required. Thus, a target price for a general-purpose 2x3 cubby storage system was set at \$100.

When Rubbermaid expressed interest in the product concept, a cost analysis and estimation were conducted to determine the feasibility of producing the desired designs, before any further prototyping or low-volume runs were contracted. As extrusions are new to Rubbermaid's capabilities and prototype panels could not be immediately manufactured for trial testing, cost analysis became the main focus of negotiations. Through its own internal marketing studies, Rubbermaid established a sales price of \$69 for a 2x3 cubby array of 1.5ft. square cubbies at 2ft. depth. In negotiations and consultations with Rubbermaid sales, marketing and engineering personnel, this \$69 ceiling became a lower target for the Cubbeez™ system.

Rubbermaid considered the greatest initial product potential in the garage storage market niche. This niche included the organzation of Rubbermaid storage bins requiring 16″ to 18″ of internal space, as discussed in the example of Section 5.2.4. Selection of a material and dimensioning the panels to accommodate the containers followed the guidelines and issues of Sections 5.2.4 and 5.2.5, with the added challenge of meeting cost goals.

Markups

Two principal factors affect the sales price of a consumer product such as these plastic consumer products: markups and material cost. Markups are the increases to cost or price added by participants in the production chain before an end-user purchases the product. In this case, there are three markups: manufacturer, Rubbermaid, and retailer. Discussions with various manufacturers revealed an industry practice of a markup factor of 2 (100% markup) by extruders for large product volumes. That is, a manufacturere would charge twice the material cost to make the product, to account for operating expenses, costs of doing business, and profits. Typical company and retailer markups vary from 1.30 (30% add-on) and higher. For the cost analysis, the Rubbermaid and anticipated retailer markups were pinned at 1.35.

Cost of Material

For plastics, including PVC and polypropylene, several materials are used in the extrusion mixture. These include: virgin resin; regrind or reclaim; fillers; and additional binders, colorings and additives. The principal material is the resin, the most expensive component, and the source of the extrusion material properties and behavior.

Although subject to availability and commodity price fluctuations, the price of virgin PVC resin is on the order of $0.40 per pound, according to industry trade magazines and published sources such as *Plastics News*. Regrind is about half the cost of virgin resin, unless sourced internally from a manufacturer, in which the effective cost is lower. As a benchmark, PVC pipe in its common pipe form *sells* for about $0.75 per pound. Although this pipe material is a lower-grade, general-purpose polyvinyl compound with basic additivesand fillers, an approximate cost evaluation leads to a source material cost of less than $0.30 per pound of material, including resin and other additives, before manufacturer and retailer markups. Weighing and calculating the price per pound of other commercially available vinyl products yieldequivalent values. A material cost of $0.50 per pound of PVC and similar plastics is estimated.

Panel Material Volume

From the example panel design of Section 5.2.4, it was determined that a quarters-scheme of fractional panels would accommodate the large Rubbermaid storage bins with full-width panels, as well as smaller objects with the fractional widths. Consulting with plastics extruders, an outer wall thickness of 1mm and an inner truss segment thickness of 0.75mm were deemed adequate and manufacturable. A breakdown of the panel design into cross-sectional areas and resulting material volumes is given below in Table T5.9.

full panel width	18.91″ (480mm)
internal width	18.11″ (460mm)
panel thickness	0.7874″ (20mm)
extruded depth	24″
outer wall thickness	0.039″ (1mm)
truss segment thickness	0.030″ (0.75mm)
volume of wall members	52.4 cubic inches
barb wall thickness	0.059″ (1.5mm)
volume of joint features	4.19 cubic inches
total material volume	56.6 cubic inches

Table T5.9: Material volume of a full panel based upon selected panel dimensions.

Cost Evaluation

Given the above values for markups, material costs, and material volume requirements, an estimation of product cost may be generated. Table T5.10 shows the cost estimates for use of polystyrene and for polyvinyl chrloride.

	polystyrene	PVC
total material volume	56.6 cubic inches	56.6 cubic inches
density of material	0.036 lbs./in.^{3}	0.051 lbs./in.^{3}
total weight of panel	2.04 lbs.	2.88 lbs.
cost per pound of material	$0.50/lb.	$0.50/lb.
manufacturer markup	x 2	x 2
cost from extruder	$2.04	$2.88
Rubbermaid markup	x 1.35	x 1.35
retailer markup	x 1.35	x 1.35
price per panel	$3.71 per panel	$5.26 per panel
panels req'd for 2x3 system	17 panels	17 panels
Sales price of 2x3 system	$63.07	$89.42
cost of req'd terminators (14)	$1.92	$2.72
total system price	$64.99	$92.14

Table T5.10: Cost estimates for Cubbeez™ system from polystyrene and PVC.

Table T5.10 shows that the polystyrene storage system meets the Rubbermaid-established $69 ceiling for a low-cost 2x3 cubby system. The PVC version, at $92, is easily below the baseline of $100, established by comparing existing storage systems on the market.

Rubbermaid, however, felt that polystyrene did not provide adequate chemical resistance. Gasoline and other solvents, for example, would seriously degrade the polystyrene; hence, this apparent solution was rejected. The PVC version, however, did not satisfy Rubbermaid's price goals. Even when considering talc-addition and large-volume resin purchases, the cost estimates were not low enough to justify product adoption.

New Process Consideration

In trying to overcome the material volume and cost issues, the idea of using microcellular plastics technology was considered. Microcellular plastics are plastic materials with micro-sized voids introduced during extrusion. The voids are orders of magnitude smaller than the smallest characteristic dimension of the extruded geometry, so the resultant material is practically homogenous and effectively continuous like the original non-porous material. With this process, the extruded product can be significantly lighter and use less actual material with the addition of these voids. Although the material properties decrease in proportion to the porosity of the material, the panels as designed provide adequate strength and stiffness for typical loads.

Trexel, a company specializing in the application of microcellular plastics to products, considers the extruded panels a potential recipient of the new processing.

Table T5.11 shows the effect of microcellular plastic porosity on the overall cost of the PVC storage system. With 30% porosity, where 30% of the overall volume are voids and 70% of the volume is the plastic, the required material volume drops by 30%, and hence the cost drops by 30%. Given the previously mentioned markup factors, panel dimensions, and and material costs, 30% porosity PVC satisfies the desired Rubbermaid price level.

	PVC, 0% porosity	PVC, 30% porosity
total material volume	56.6 cubic inches	56.6 cubic inches
original density of material	0.051 lbs./in.^{3}	0.051 lbs./in.^{3}
density after porosity effect	0.051 lbs./in.^{3}	0.036 lbs./in.^{3}
total weight of panel	2.88 lbs.	2.02 lbs.
cost per pound of material	$0.50/lb.	$0.50/lb.
manufacturer markup	x 2	x 2
cost from extruder	$2.88	$2.02
Rubbermaid markup	x 1.35	x 1.35
retailer markup	x 1.35	x 1.35
price per panel	$5.26 per panel	$3.68 per panel
panels req'd for 2x3 system	17 panels	17 panels
Sales price of 2x3 system	$89.42	$62.58
cost of req'd terminators (14)	$2.72	$1.90
total system price	$92.14	$64.48

Table T5.11: Effect of microcellular plastics on PVC storage system cost. 30% porosity brings the cost of a PVC system below the desired baseline set by Rubbermaid.

However, while these cost estimates imply that the modular storage system satisfies the conditions for production, the actual manufacture of the product would require more detailed analysis and testing. The microcellular plastics process is not yet in large-scale production for this type of application, and the tooling and fixturing required in addition to the primary extrusion tooling are also challenging tasks.

In addition, the start-up cost of a manufacturing facility must be justified by more detailed market and company studies.

5.3 Modified Management Tools

Finding a market-in, as discussed in the previous section, is often a time-consuming and difficult task. Whether done by individuals and small enterprises or by established companies, the ability to evaluate and manage innovation activity is key towards the product's, and the innovator's, success.

In the field of management of innovations, there is considerable material about how teams and company management classify, categorize and react to market pressures, new technologies and innovations. For example, management evaluative tools can assist in identifying innovations by their relationship to current embedded knowledge bases and linkages between technologies. This kind of exercise sheds insights on companies' abilities to take advantage of their resources to either move forward with the innovation or to protect themselves from competitors' actons.

However, there are few established tools that can be used by the individual innovator or entrepreneurs seeking insights in the marketplace, yet they are a group that needs these evaluative frameworks the most, as they have fewer resources and a less extensive operating base. This section introduces and modifies existing management tools so that they are more usable to the individual, then applies the modified forms towards the case-study project on modular storage systems.

5.3.1 The Transilience Matrix

The original transilience matrix is based upon evaluating the capacity of an innovation to influence established production and marketing systems.[29] It maps innovations into a two-dimensional space defined by two axes: the product market and customer linkages, and the technology and production environment.

Modifying the Transilience Matrix

Fig. 5.66 shows the basic transilience map with its four quadrants of innovation type: niche creation, architectural, regular, and revolutionary. An innovation can be identified as one particular innovation type by its anticipated or interpreted effects on the market and the thechnological environment. While the mapping of a particular innovation may be difficult or could be placed in various locations in the map, the exercise of evaluating the innovation and the marketplace is the real objective of using the transilience matrix.

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[29] Abernathy, W. and Clark, K. "Innovation: Mapping the Winds of Creative Destruction," *Research Policy*, 1985.

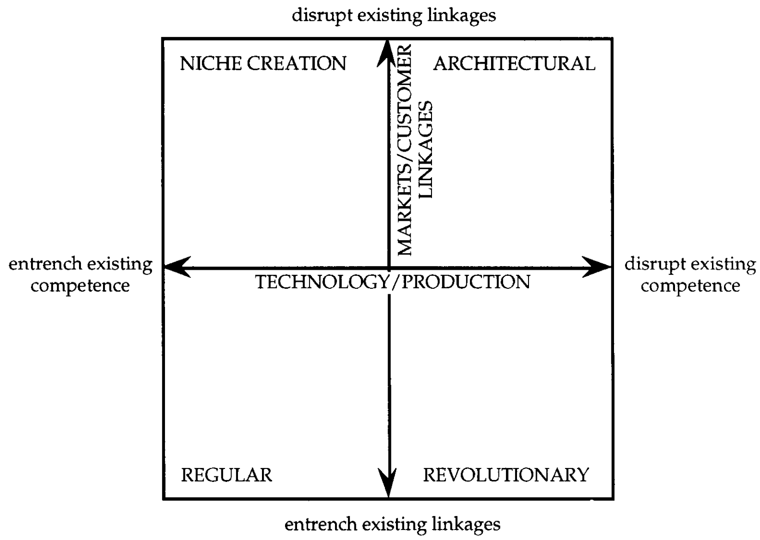

Fig. 5.66: The transilience matrix as proposed by Abernathy and Clark. Innovations can be identified by its effects on the existing market linkages and technology base.

For an individual innovator, however, often there is no established market linkage for the innovation, whereas a company may already have these links and criteria for operating with their customers. Hence, for the individual without a company sponsor, the market axis is not well defined.

As a result, however, the transilience matrix can be used as a strategy planner. If the inventor can determine if the innovation may either disrupt or entrench current technologies or industry competencies, then the innovator can then map possible market scenarios – e.g. should an technology-disruptive innovation be pushed as a revolutionary product, using current marketing channels, or should the same innovation be coupled with a novel approach to marketing and new customers. Similarly, if the innovation can be developed as either technologically entrenching or disruptive depending on the product application, for example, the innovator can focus on the transilience sector more likely to meet the individual's goals. These issues are reflected in a modified transilience layout, shown in Fig. 5.67.

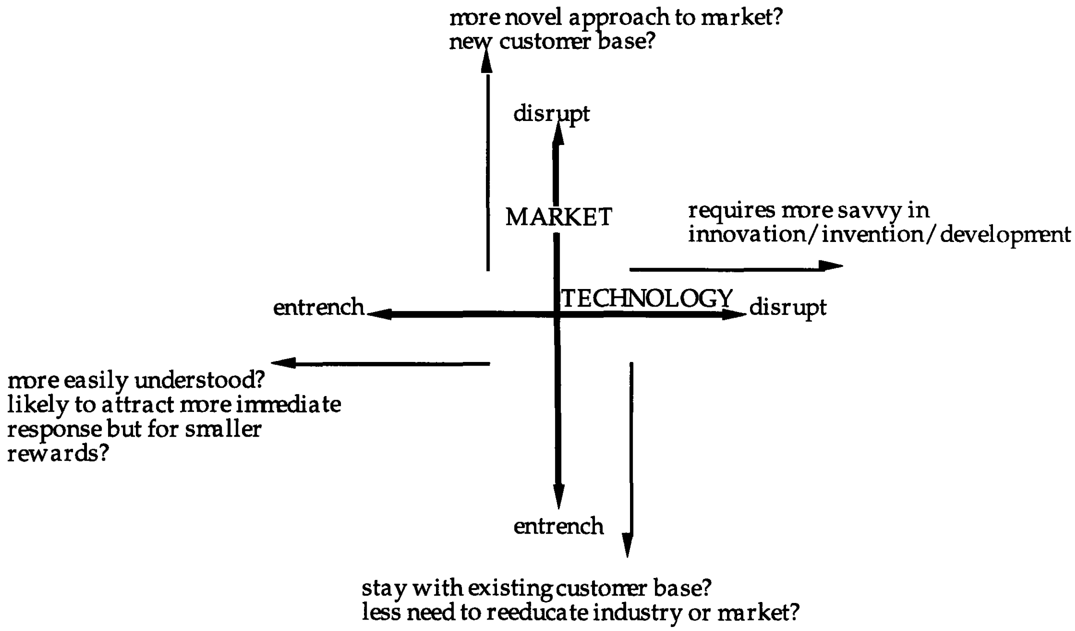

Fig. 5.67: The modified transilience matrix and questions for individual innovators. Anticipating market possibilities allows innovators to determine how to seek a market-in.

The greater weight of personal risk in managing an innovation makes this scenario-identification process more important to aspiring entrepreneurs. While a company may not want to produce a technologically-disruptive product in a market-disruptive setting because of the inherent difficulties involved in creating new linkages, an individual may actually want to strive for architectural innovation because of less competition in that particular environment. Of course, the individual may want to stay within current market channels if the likelihood of successfully forging new relationships is slim.

Hence, the transilience matrix can be used by the entrepreneur in mapping existing innovations and seeing where the opportunities lie within the quadrants of technology and market links. Instead of mapping in hindsight the possible classifications of a given innovation, the individual can identify where the innovation can succeed, and identify possible multiple applications and industries in which to enter.

Applying the Modified Transilience Matrix

The modular design of the Cubbeez™ storage systems can be compared to existing products in a "one-dimensional" transilience matrix, shown in Fig. 5.68, a matrix without a well-defined market axis, based upon physical and manufacturing traits (technological aspects).

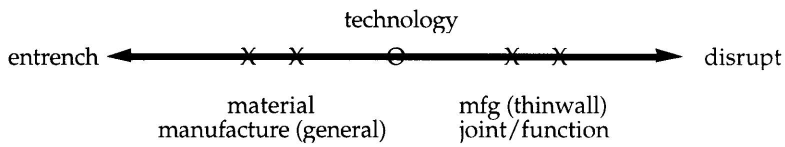

Fig. 5.68: A one-dimensional modified transilience "matrix" using only the technology axis.

The storage product may seem ordinary because it can be made of common materials, especially plastics and fiber-filled plastics. Also, other products, not in the storage market, are currently made using an extrusion process, the likely process to make the new product. Potential end-users may be the very same users of the crates: those in middle-class homes, young adults, and apartment renters.

On the other hand, the innovation calls for some new details in manufacturing, including more precise dimensional control (exacerbated by the long aspect ratio of the panel cross-section and the thinwall segments). Also, the method of attachment is new; no joint centerpiece or structural frame is needed. The new joint is in a new class of interfaces -- multifold rotationally-symmetric mating. Thus, the innovation can include a combination of old (common) factors as well as new ones for the industry.

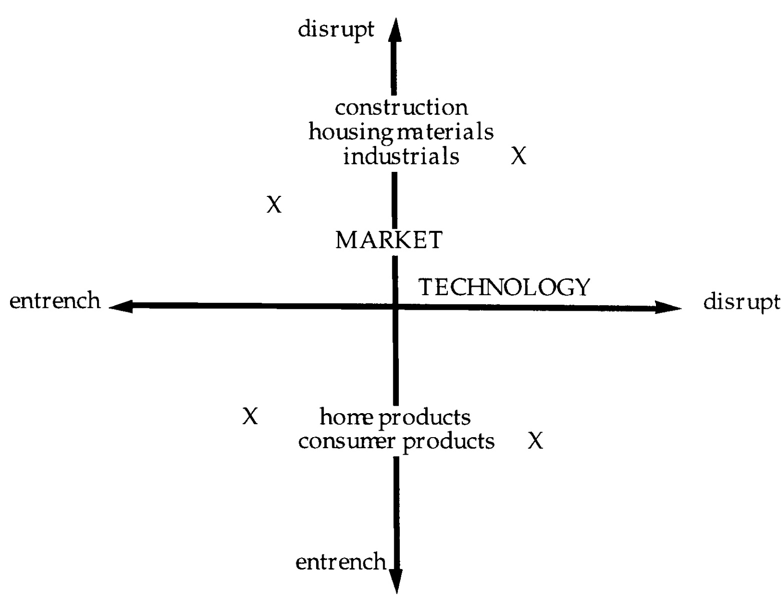

Fig. 5.69: The addition of the market axis for scenarios of the modular storage products.

The above discussion applies to only one possible product embodiment (application and associated customer) for the invention. The lack of a company background, and thus a lack of management directive or specified direction, allows us to explore targeting other customers with the same invention. Adding the second axis to the one-dimensional transilience matrix of Fig. 5.68, we may consider other markets and customers than the typical end-user for crates, as illustrated in Fig. 5.69.

Retailers and industrial users needing storage solutions can be benefit from the product; perhaps building and construction industries can use the invention in non-storage ways (e.g. a structural use). Some of these markets may be considered disruptive to an existing company; some plastic product companies focus on domestic products, while others focus on industrial purposes.

5.3.2 Core Competencies and Linkages Between Them

Analyzing an innovation as a combination of the technologies used to produce it as well as how those technologies were coordinated is the basis of another innovation-classifying matrix.[30]

Modifying the Competency-Linkage Matrix

Fig. 5.70 shows the original matrix classifying innovations by the nature of the core competencies used for the innovation and the linkages between those core concepts.

linkages between competencies \ core competencies	reinforced	overturned
unchanged	Incremental Innovation	Modular Innovation
changed	Architectural Innovation	Radical Innovation

Fig. 5.70: An innovation classification matrix based upon core competencies and the linkages between them.

[30] Henderson, R. and Clark, K. "Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms," *Administrative Science Quarterly*, 1990.

Identifying the core competencies and how those competencies are combined in a product innovation determines the type of innovation as an incremental, modular, architectural or a radical innovation. This classification matrix can be used by the entrepreneur to identify areas within industry or within a specific company where an innovation can be used. As an outsider, so to speak, the entrepreneur can evaluate the structuring of expertise and know-how in a field and look for new solutions that can take advantage of existing situations.

For example, should the entrepreneur identify companies which possess two different core competencies, while there is not yet a link between the two fields, then the individual may be able to find a new way to use both competencies and create that link between the companies with an innovative product or marketing strategy. By using the framework tool, as outlined in Fig. 5.71, the entrepreneur can also determine what a given innovation will require — if the innovation is incremental, then there are more immediate avenues to take to produce the new innovation, as opposed to a radical innovation idea which may require more extensive research and argument.

	core competencies	
linkages between competencies	existing	insufficient
exist	does a company already exist for this innovation?	needs new (process) innovation?
not yet connected	new link needed, by (product) innovation?	a drastic set of innovations to revitalize industry?

Fig. 5.71: Identifying opportunities by considering core competencies and their linkages.

As with the transilience matrix, this framework can be used by the innovator as both an idea catalyst (to identify areas ripe for innovation) and for analyzing a new invention yet without resources and a market.

Applying the Modified Competency-Linkage Matrix

Is there an opportunity with the Cubbeez™ project for a new business venture? Consider two markets -- those of home storage solutions (e.g. makers of crates and containers) and those of thinwall housing materials like siding and decorative paneling. Clearly there are similarities between makers of plastic containers and of plastic siding, and extensive knowledge about plastics production overall. How about any combination of the two fields, and their expertise, for a new product line? Who combines the two product embodiments, each having relatively distinct applications and features?

We found there exist few companies that bridge the gap between "crate" and "thinwall" products. This void in the matrix, as shown in Fig. 5.72, in the architectural quadrant, seems like an opportunity. Relatively little new knowledge in industry must be found, but the link between the distinct plastic sub-fields needs to be established to produce the proposed product.

linkages between competencies / core competencies	**existing**	insufficient
exist	e.g. lower material costs and mfg costs	e.g. new plastic compound introduced
not yet connected	**e.g. new product and company**	major changes

Fig. 5.72: Scenarios for the plastics example using the competency-linkage matrix.

The production of thinwalled structural paneling in aluminum as opposed to plastic is an example of an overturned competency. Due to material and process differences, production of thinwalled aluminum requires much more development work; current precision extruders consider the panel cross-section currently impractical and not feasible because required dimensions and tolerances are not within their capabilities. Hence, an *incremental* or perhaps a *modular process innovation* is required in order to achieve the aluminum product innovation; aluminum extrusions for both containment and structure already exist, and the link between these competencies mostly exists.

5.3.3 Technology Curves and Timing Lines

Technology curves are typically used to review past achievements in a technology and to discern if improvements are asymptotically slowing in growth. A review of technologies show that the so-called "paradigm shifts" occur when the outdated technology slows growth, and the new technology encounters augmented growth.

Applying Technology Curves and Timing Lines

The concept of a technological limit is applicable to the inventor or individual innovator in a slightly different way than is typically used by the S-curves and performance curves of Foster[31] and of Christensen.[32] While these means of illustrating some relative performance parameter over time can be helpful to the innovator, it is less likely to be easily determined, due to the limited market research resources available to an independent person. Yet it is conceivable that a non-company member as a consumer or end-user can anticipate a radical shift and capitalize on the observation before an industry can.

When considered in conjunction with the timing line, the ideas of approaching limits and impending shifts can be taken to heart by the small innovator with an idea: when the idea becomes more incrementally improved as opposed to being transformed by leaps and bounds, perhaps the innovation design is nearing its optimal time to be patented (and licensed), advertised or considered "mature" in the pre-market design stage. That is, when developing an idea, say, specifically for a patent application, an inventor needs to be aware of the breadth of the idea versus the trade-offs of time- and resource allocation. Keeping in mind the personal risks at stake, the inventor cannot spend all resources developing the idea because eventually the idea must be acted upon — by patenting, more market research, etc. — which also require resources.

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[31] Foster, R. "Timing Technological Transitions," in Horwitch, M. (Ed.) Technology in the Modern Corporation, a Strategic Perspective, 1986.
[32] Christensen, C. "The Limits of the Technology S Curve," *Production and Operations Management*, 1992.

In the case of patenting, although the United States still recognizes the first-to-invent, other countries do not. Thus, timing is important. Even in the United States, unfortunately, proving first-to-invent may be difficult for the small innovator should a large company challenge that claim. While not ethically-sound, this kind of corporate maneuvering is not unheard of in the fight for intellectual property. The risk of "being late" with an idea can be sizable for the independent innovator. But file too early, and the clock begins ticking for filing internationally, and for financing the international patent applications which can reach the tens of thousands of dollars for multiple countries.

Foster identifies an indicator in "detecting decay" in a company's innovational pursuit. One point, when there is "a tendency for significant variations among competitors in R&D spending to produce ever less significant results," seems linked to the emergence of "me-too" competition.[33] For example, the ever-present "milk crate" can be found in countless forms and designs. Yet practically all of the containers exhibit similar functions and are made using the same manufacturing process of injection molding. Whoever first produced these ubiquitous crates was easily copied, and today there is little difference in performance of any container on the market.

Consider the S-curve issues, and the dominant design paradigm[34] to the crate example. The basic design of the crate container is relatively unchanged from the early models. It has five sides of a cubic structure, consisting of webbing and ribs, and with some number of features like handles and stacking protrubances. The original intended purpose of the crate was probably to hold and carry objects (e.g. milk bottles) and to be stackable. To this end, current crates all perform those functions well. However, as customers demand more and discover new desired uses for products, the dominant crate design has performed poorly, in this author's opinion. For example, crates stacked on their sides buckle under typical loading. Also, arrays of crates tend to be unstable, as there is no rigid connection between sides of crates without the addition of parts and connectors.

The production of these products has become more of a *process* challenge – minimizing material volume and hence costs through optimizing the design for injection molding.

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[33] Foster, R. 1986.
[34] Teece, D. "Profiting from Technological Innovation: Implications for Integration, Collaboration, Licensing and Public Policy," in Teece, D. (Ed.) *The Competitive Challenge*, 1987.

The design of the crates has *matured.* On the simple consideration of these observations, is the emergence of another storage system on the market expected? Fig. 5.73 illustrates various S-curves for the storage system and crate comparison.

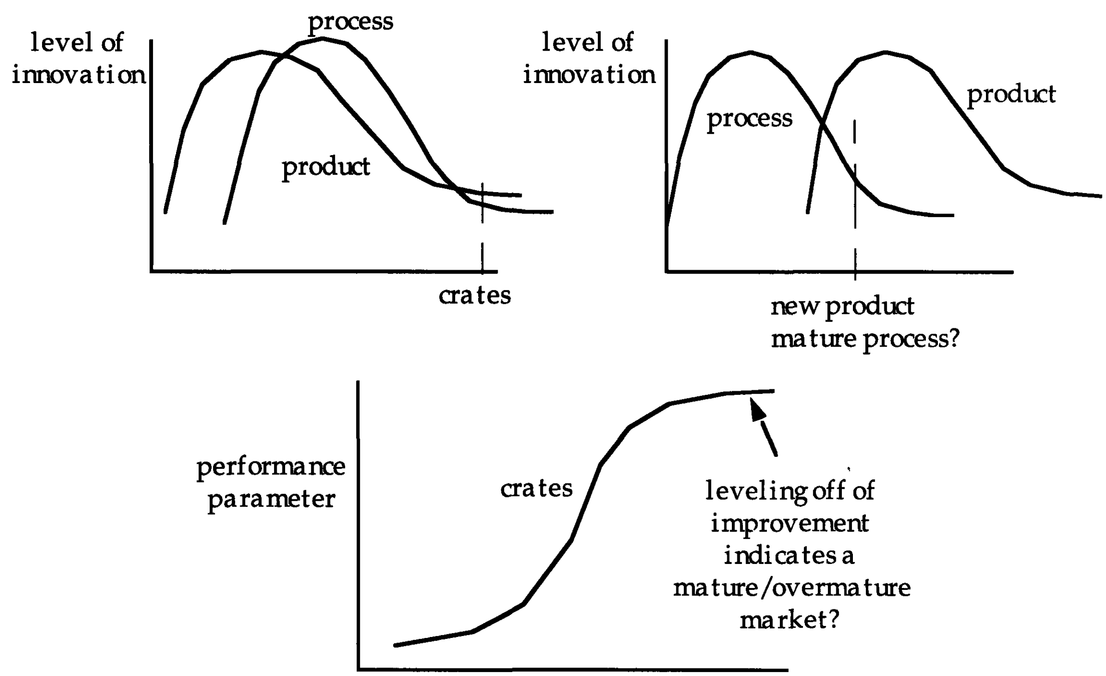

Fig. 5.73: Possible performance curves for the crate example.

Hence, viewing the existing, mature design of crates, and comparing the proposed modular storage systems in this context, there appears to be support for a new product opportunity.

5.3.4 The New Business Matrix

Companies looking to new technologies often acquire other firms or enter in joint ventures to develop other innovations. How a company determines which option is most viable and least risky is of major interest to new product firms in a fast-paced, ever-changing technological industry. Roberts and Berry discuss the issues behind companies expanding themselves through business opportunities, whether the technologies and markets be new or familiar.[35]

[35] Roberts, E. and Berry, C. "Entering New Businesses: Selecting Strategies for Success," *Sloan Management Review*, 1985.

Modifying the New Business Matrix

For budding entrepreneurs, being aware of these same issues when forming a strategy for an innovations is key for being sponsored or backed by an existing company. By analyzing the market and determining what other players are competing, the entrepreneur can position its activity in such a way that it be attractive to joint venture, buyout or some other collaborative activity with an established company.

A modified 3x3 matrix illustrating the market and technology axes, and the newness of the innovation on those axes, should be understood by the innovator as well as by the companies considering new business opportunities. A general new business matrix for the innovator is given in Fig. 5.74.

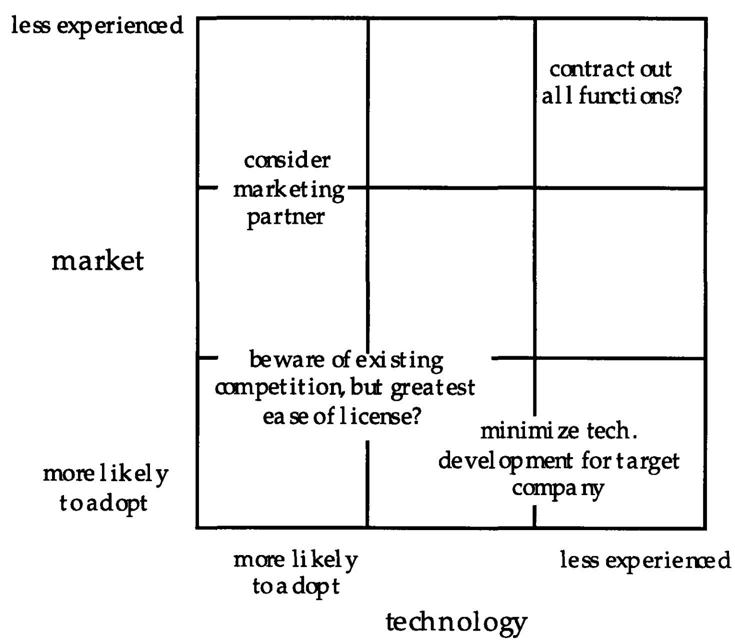

Fig. 5.74: A modified new business matrix for the innovator and entrepreneur.

For the individual entrepreneur, developing an innovation and making it accessible to large companies will enhance the chances of a company actually appropriating the innovation. Clearly from the discussion of Roberts and Berry's strategies, an innovator seeking industry attention needs to be aware of the likes and cautions of companies in committing to new business. Also, since companies viewing the innovation will place the development in different matrix cells, the innovator may be able to package the innovation in appropriate ways to help convince the company to further consider a new venture. Failing to see what pitfalls the companies want to avoid and disregarding what they refer to do can be considered as essentially not doing one's market research.

Care must be taken, however, when modifying the innovation to suit companies' desires; the individuals responsible for the innovation must make sure the strategy and possible outcomes are acceptable for themselves. That is, if analyses deem that a start-up company is necessary in order to be acquired by a larger company, the individuals must be committed to start-up. Otherwise, the risks and requirements involved may be contrary to personal goals and acceptable risks, and for those reasons, a start-up may not be the best overall goal.

Applying the Modified New Business Matrix

What form of business can be entered? Is a license given out? If yes, then to whom? If no, is a new company the solution? To answer these questions, the modified new business familiarity matrix can be used, as shown in Fig. 5.75. In the outermost corner element, there exist companies rather unfamiliar both in the technology and in the market. This type of company does not usually deal with consumer products, but is considering an attempt. For the firm to enter an industry so mature in plastics manufacturing technologies and markets seems quite inadvisable.

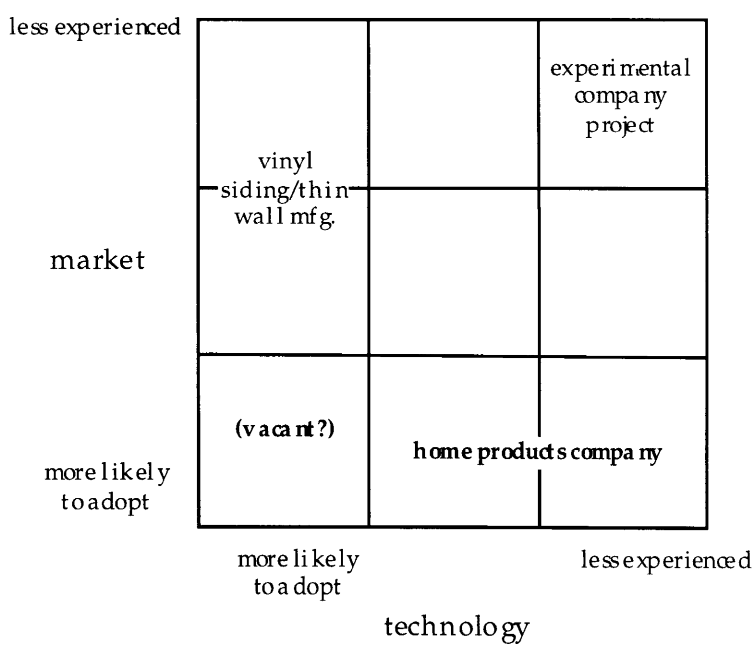

Fig. 5.75: Targeting of innovation using the modified new business matrix.

Extruders of vinyl siding, such as CertainTeed and Georgia-Pacific, are experienced with the technology required to manufacture the thinwalled structural panels, but are less familiar with the home consumer market. These companies are positioned in the upper left region of the matrix. A consumer product company, a maker of storage bins such as Rubbermaid, for example, is quite familiar with the market and the large potential customer base, but the manufacturing requirements, such as thinwall extrusions, are unfamiliar. These types of companies appear in the lower right corner of the matrix of Fig. 5.75.

The apparent vacancy in the lower left corner of the matrix, that of a venture central to an existing company on both technological and market factors, could be a promising sign. This may imply that there are no companies identified that currently produce this kind of product.

5.3.5 Complementary Assets and Knowledge Assets

An important difference between a company project and an individual's project in innovation is that the risks are much more personal for the individual. Hence, available complementary assets[36] are considered, and those that are missing require more attention. In this example, the number of complementary assets possessed by the involved individuals are few. The possessed assets of the modular storage case-study inventors are (pending) patent protection and the MIT name and reputation. There is also experience in licensing tactics. From experience and previous ventures, a business network in the legal field is established. However, building a new company without possessing many other assets would require the partnering with a company with a greater portfolio, or finding a way to obtain those missing assets.

Even if a start-up company is a valid option based upon the framework analyses, the reality of the decision-making process depends finally on the individuals' goals. Neither person involved is willing to bear the significant burden of committing all resources into obtaining missing assets directly. Thus, use of the modified management tools must always be considered with personal issues.

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[36] Teece, D. 1987.

Considering intellect and knowledge as assets complicates the picture of complementary assets. Here it is assumed that the inventor and developer of an innovative concept and application knows the particular details and design issues better than any company that is interested in the idea. Given the desire to protect the idea, whether by patent, trade-secret or other means, how may an innovator protect intellectual and knowledge assets while sharing aspects of the innovation with potential partners or licensees?

The discussion of knowledge as ranging from "difficult to transfer" to "easy to transfer" as outlined by Winter[37] raises concerns for the entrepreneur on appropriability. Is the idea too vulnerable to copying, stealing or "me-too" competition? For the innovator, plotting the concepts using such a taxonomy, or at least being aware of the issues, can influence the decision to patent, hold secret or seek further protections of the intellectual property.

For example, if the idea is "observable in use," then patenting or perhaps copywriting may be most appropriate; additional broader coverage may be pursued through broader claims. However, if the innovation is not easily analyzed, like a complex chemical composition or process, then maintaining a trade secret is more likely to protect the innovation and therefore also the innovator. The case study example is of the former type, where a set of design concepts and applications are easily copied, and a patent most appropriate for protection.

Knowledge as an asset is a major influence in evaluating options. From the very beginning the innovations were seen as patentable, and necessarily so. The nature of the invention is "easy to transfer" because of the high design content and geometric properties. Patenting provides initial protection, and company sponsorship or licensing for a corporate protector is a greater option. But even beyond the knowledge of the innovation, the knowledge of analysis for innovations, as represented by the course framework and tools, is a critical asset to have as an innovator and hopeful entrepreneur.

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[37] Winter, S. "Knowledge and Competence as Strategic Assets," in Teece, D. (Ed.) *The Competitive Challenge*, 1987.

5.3.6 Conclusions for Using Modified Management Tools

It has been hypothesized that the concepts of managing technological innovations can be applied to managing individual's innovative activities. It seems, at least with the case study in progress as an example, that similar issues are raised regardless of the source of the innovation or the party raising the concerns.

Since the resources available to an individual are fewer than those of a company practicing research and development and encouraging innovations in products and processes, the frameworks involving asset management and allocation are less obviously applicable. However, consideration of assets is the evaluation of strengths and weaknesses, advisable for any entrepreneurial effort.

Positioning oneself to maximize the success of an innovative idea is key to finding the right opportunity for a new venture. Whether it be by licensing or by company start-up, knowing more about the pitfalls and the competition is important, and the use of analytical tools and modified frameworks for discussion can be effective ways to reveal the risks and the market.

Chapter 6

A Model for Product Innovation Research

From the lessons from the research projects of Chapters 4 and 5, a model for Product Innovation Research can be outlined. Though there is no guarantee that product designs will reach the market successfully as a result of the proposed guidelines, the organization of the innovation efforts will lead to greater numbers of research efforts. This research, the opportunities resulting from research, and the education gained from conducting the research, will remain as valuable contributions to the university and the students.

Section 1 discusses the environment today at MIT that favors formalizing product innovation activities, in terms of available resources and support. Section 2 outlines important steps which groups should be aware of as they conduct innovation research. Organization of participating members, sources of information and recommended tasks are discussed. Section 3 considers ways in which the program can be formalized and implemented within MIT and the Department of Mechanical Engineering. Section 4 suggests ways in which students can publicize their innovations to the university and others. Section 5 suggests additional resources that would further facilitate innovation research. Section 6 cites issues which may limit the effectiveness of a Product Innovation Research Program.

6.1 Why Now?

Much of the accomplishments of the projects summarized in Chapter 4 were made possible by the greater access to resources, complementary activities to innovation, and general support by Institute members for product innovation and educational changes. This seems to serve as the ideal catalyst for expansion and formalization of the effort.

6.1.1 Improved Resources

In the engineering community, as well as in MIT itself, the level of sophistication and capabilities of resources have improved greatly in recent years. Improved resources, and increased student access to those resources, are key components for product innovation. Having resources decreases the waiting time students must endure before getting results, whether they be analysis data, graphical representations or hands-on prototypes.

Computer Resources

Competency in computer software for engineering and design is becoming more and more desirable for practicing engineers in industry. However, the availability in software applications and the basic education in these programs have been limited or scarce in the past. Recent improvements in the usability and interface of industry-standard packages allow beginning users to conduct useful computer-aided design and analysis. At the same time, through university provision, the software is available to students, and recent additions to core curriculum coursework have made the programs less foreign to students.

For example, Pro/ENGINEER™, a professional computer-aided design package, is available for student access on the MIT Athena computer system. To support this alternative to AutoCAD™, another department offering, Pro/ENGINEER™ has become a central element of a required undergraduate course 2.670. With AutoCAD™ and products like MasterCAM™, a computer-aided manufacturing program, the tasks of computer modeling and interface with machining centers are more readily available and supported at MIT than ever before.

In addition to "student-public" applications, research groups within departments have limited-seat licenses to complementary software packages. The Product Engineering Research Group (PERG), also known as Precision Engineering Research Group) in the Department of Mechanical Engineering, has its own licenses to Pro/ENGINEER™ as well as Pro/MECHANICA™, one of several optional analysis modules complementary with Pro/ENGINEER™. Another package, SDRC I-DEAS™, is another parametric modeling package available to PERG members. For rendering purposes, programs such as Photoshop™, TriSpectives™ and QuarkXpress™ enable the research students to produce professional illustrations and layout for documents, brochures and press releases.

In addition to software, computer hardware is being acquired by the department for various production purposes. For example, a scanner can be used by department members for portfolios and presentations. Research groups may also have the appropriate hardware.

Machine Shops and Laboratories

MIT's Department of Mechanical Engineering can boast of two major machine shops and a prototyping shop in addition to other smaller shops for particular research areas. The Pappalardo Laboratory, opened in 1995, houses the department's main machine shop and instrumentation labs. It features a wide range of machine tools for most engineering materials, with full-time shop management and machinists. The Building 35 machine shop, of the Laboratory for Manufacturing and Productivity, also has its complement of machine tools as well as numerically-controlled (NC) machines, including NC lathes, an NC mill, a hexapod machining center, a thermoformer, an injection molder and an abrasive waterjet-cutter. The department's Prototyping Lab also has resources for the design and fabrication of mock-ups and prototypes.

Telecommunications and Internet Services

The predominance of computer resources at MIT provides more than computer software applications for engineering. The network capability and the presence of Internet services makes telecommunication a standard among all students. With the increasing numbers of companies also using online services to gather information and to publicize their products and services, MIT is well prepared to benefit from the telecommunication advances of recent years.

Tasks such as electronic mail and networked groups allows students, staff and faculty to conduct research and share information without geographic co-location. Add to the Internet capabilities, facsimile transferal of information and the basic telephone allow students to keep informed of their work and the latest developments in projects and technology around the clock.

The World Wide Web itself is a boon to product innovation research efforts. Sites provide critical components of development and marketing tasks, including company profiling and patent research. Without such access, a patent search can take many times as long to complete, due to limited library hours, microfilm reader availability and the slower processing and selection of information. Patent research online is discussed in Section 6.2.6.

6.1.2 Complementary Activities

As briefed in Section 2.1, MIT supports activities that complement and are complemented by product innovation research. In particular, the following recent efforts and programs fit well with the objectives of the Product Innovation Research Program.

Course 2 Mechanical Engineering:

- The new Course 2 Mechanical Engineering Curriculum – course requirements and electives revised in 1996 to reflect a more integrated undergraduate education.
- Continuation of 2.670, the required IAP course for Course 2 sophomores and a pre-requisite of 2.007, the first of a three-course Design and Manufacturing stream. Basic machining and computer-aided modeling on Pro/ENGINEER™ are included within the syllabus.
- Continued improvements to 2.007, Design and Manufacturing I, in which students are making more robust and sophisticated devices in recent years.

- Greater project choice in 2.009 Product-Engineering Process, in which student teams decide upon project area and product market niche.
- The engineering and management course 2.739/15.783 in which student teams prototype new products. emphasizing market and business considerations.

Independent or Elective Courses:

- Alternative innovation research opportunities such as the IAP OME Second Summer Program, taught by Prof. Slocum, in which first-year students engage in invention, design and development.
- Freshman seminar by Prof. Slocum, in which students are encouraged to select a product area in which to invent and innovate.

Growing Incentives for Innovation:

- The $50K Competition, which has grown in a few years from the $10K Competition.
- The Lemelson-MIT Student Award, now entering its fourth year.

Program Proof-of-Concept Evidence:

- Three consecutive R&D100 Awards by Prof. Slocum and PERG members, on projects with significant market input and considerations.
- Two Lemelson-MIT Student Award winners from the PERG Lab.
- Numerous pending and issued patents as a result of precursory case-studies of the proposed Product Innovation Research Program, as summarized in Chapter 4.

These courses, incentives and activities all serve as important complements to product innovation. As other services and resources become available, product innovation research will become that much more realizable and effective.

6.1.3 Multiple Audiences

As a result of the IAP OME Second Summer Program, PERG research and the accomplishments of Prof. Slocum, the proposed Product Innovation Research Program is gaining wider recognition. At this time, support is sought from numerous bodies, including : the President's Office; Alex d'Arbeloff, MIT Corporation Chairman (as of July 1997); School of Humanities; Department of Mechanical Engineering, including the new Center for Innovation and Product Development; and outside companies.

Already, as the case-studies progress and start new business ventures, the audience for Product Innovation Research grows as the network of participating companies grows. As it is also related to the Urban Design Corps, more of which is described in Chapter 7, innovation research will have broader outreach beyond the engineering and university community.

6.2 Steps for Developing Innovation Research

Innovation research requires a well-defined and methodical approach. As discussed in Chapter 3, designing a proper Design-Development-Marketing organization and positioning it within an existing university structure are essential to the effectiveness of the research.

6.2.1 Organizing Students and Faculty

While no one formula for organizing individuals for product innovation or design exists, the precursory case-studies of Chapters 4 and 5 show that the product innovation research should exhibit student-driven leadership, with graduate student and faculty member guidance and motivation.

As the research activities are meant to give the *responsibility* to the innovation students, care must be taken when organizing the participants so as to delegate enough *authority* to the students. Otherwise, the students lose "ownership" of the project, and instead the project "belongs" to the directing professor. If this is becomes the case, then the student innovators may feel that they have lost control of their own inventions and also their "stake" in it as well.

Recognizing that a "piece of the action" and "ownership" are key benefits for the students involved, these features must be protected. Proper organization and job roles should be established so that parties understand their primary responsibilities. Here is a basic outline for the product innovator team members:

- Faculty champions
  - Take active mentoring roles in projects
  - Motivate students to take assertive, pro-active roles
  - Contact industry representatives and contacts
  - Suggest project design options, alternatives
  - Co-develop

- Graduate student managers (if with an undergraduate team)
  - Guide, teach, co-develop
  - Help delegate and direct tasks
  - Form peer relationship with fellow students
  - Introduce team members to resources and references
  - Check schedules and deadlines
  - Suggest project design options, alternatives

- Student Teams
  - Conduct and lead innovation research efforts: designing, developing, marketing, patenting
  - Knock on doors, interview, perform market research
  - Produce outreach material: brochures, advertisements, press releases, samples or prototypes
  - Learn by doing, creating, integrating

By organizing the efforts around people and the products, and by giving each person a share in the project ownership and a stake in its successes, the innovation research can be sustainable beyond projects characterized by semester timelines and grades as rewards.

6.2.2 Thesis Team Formation

The previous discussion leads to the notion of *thesis teams*. A thesis team is an option for organizing a faculty advisor with research graduate students and undergraduate students having different skills and expectations. This concept is similar to the organization of various research groups in the university – a research topic is split into well-defined subtopics that are researched by UROPs, seniors (for thesis), S.M. and Ph.D. students, and the faculty members themselves. In each level, from UROP to faculty member, the complexity of the given problem increases, as does the scope of the research.

For product innovation research, a similar approach is used: participants are brought together for the concurrent design, development and marketing of the product concept. For example, those with more developed skills and abilities, such as modeling and analysis knowledge, delve deeper into the engineering and science aspects of the product. At each level, the corresponding supervisors are those in "higher" levels of expertise and experience.

However, this implementation of thesis teams differs from the typical form in that each level conducts essential work for the project. While one member may perform analysis, for example, and another member may be in charge of market research, neither member's work could be lost without affecting the whole project. This is consistent with the feature that all members retain partial ownership of the project.

If the research conducted by a graduate student is central to the student's degree, the topic may be more expansive upon one aspect of the product design or perhaps the process to manufacture the intended product, so the results may be more aligned with university research objectives and less directly applicable to the intended product design. However, this research may have an indirect but valuable effect on the project: fundamental new discoveries may be discovered, or the product concept and corresponding intellectual property domain may be increased and expanded upon as a result of the research. Hence the retention of stake in the project remains a valid feature.

Fig. 6.1 shows a representation of a thesis team, shown as the rounded rectangle, consisting of a faculty member (F), a graduate student (G) and a team of undergraduates (U). Note that the team is shown between "MIT" and "Industry," representing the dual environment of product innovation research. Inputs to the thesis team project may include contributions from another faculty member, graduate student or undergraduate student, as well as an industry or company participant (C).

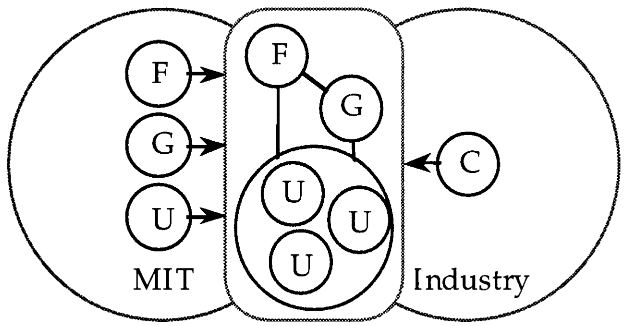


Fig. 6.1: A diagram showing a thesis team of a faculty member (F), a graduate student (G) and a team of undergraduate students (U). Information, consultation or assistance may be contributed by another faculty member, graduate or undergraduate student, or by a company participant (C).

Fig. 6.2 show other representations of thesis teams. Fig. 6.2a shows a three member team of a faculty member, a graduate student and an undergraduate student. Whereas the undergraduate team in Fig. 6.1 may be a UROP group, the undergraduate in Fig. 6.2b may be a senior conducting S.B. thesis work instead.

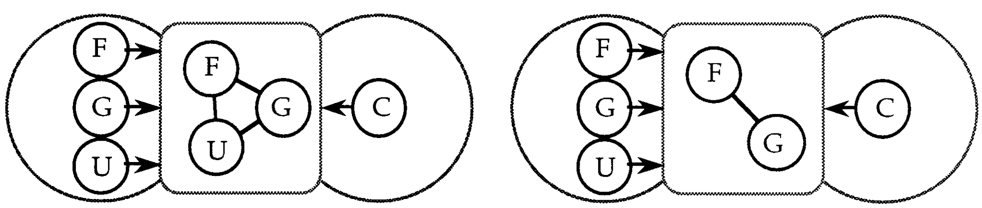


Fig. 6.2a

Fig. 6.2b

Fig. 6.2a: Another thesis team representation of three members: faculty member (F), graduate student (G) and one undergraduate student (U). Fig. 6.2b: A thesis team comprised of only a faculty advisor (F) and a graduate student (G).

Fig. 6.2b shows only a team of a faculty member and one graduate student. This may be either a faculty advisor and a graduate student pursuing the project as a major part of an advanced degree, or it may be a related project to the central research activity.

6.2.3 Selection of Elective Courses

As some members of the product team may be in the middle of their degree, the selection of electives related to the innovation project is one way of bridging islands of education.

Rather than taking an elective not linked to a central project or theme, choosing a course will be helpful to the innovation project. It is also possible that because of the innovation project, the student will learn more in that elective course than if the student were not involved in the project.

For example, for graduate students, either as co-developers or as managers for undergraduate teams, design courses such as 2.74 (Optimal Product Redesign), 2.744 (Product Design), 2.810 (Manufacturing Processes) and 2.891 (Management for Engineers), would take on greater meaning and applicability given a real product innovation effort in which the students have a vested interest. In addition, the graduate student may find an opportunity to introduce the project into the course, thereby contributing real experiences to class discussion or course studies.

For undergraduates, electives such as 2.72 (Elements of Mechanical Design), 2.96 (Management in Engineering), and 6.351 (Development of Inventions and Creative Ideas), as well as the graduate courses above, would present material that would be applicable towards a given innovation research activity. Should the innovation project require detailed engineering studies, such as fluid mechanics, heat transfer and the like, then corresponding courses can be attended.

6.2.4 Establishing a Timeline

Invention can occur at any time and require perhaps as little as a day to think of the idea. Development and market can take years and still not yield total success. To encourage regular progress and to maintain interest, an appropriate timeline should be established and re-evaluated as the project develops.

Brainstorming and decision on product area can be done within the first month. Even if the product ideas are later found infeasible or already covered by a previous invention or existing product, the process of identifying product markets is in motion.

Patent research done over two weeks serves two purposes: to check if the product idea already exists, and to discover what innovations or improvements can be made over the existing work.

After these initial activities have been begun, concurrent development of the product concept should commence. Design, engineering, marketing and patenting are core tasks that should be done together, so that one task draws information from and returns conclusive evidence to the other efforts. Other tasks may be necessary, such as fabrication, testing and manufacturing. Often times, however, the design and engineering phases of the project are more heavily practiced in the earlier stages of the project followed by a phase of market research and advertising. This market focus may become the primary focus, until at some point, information and feedback from market research affects the design and engineering aspects of the project. If this is the case, it is important to maintain up-to-date records of progress so that little time is lost when changing focus between tasks.

Whatever the project status, a timeline or Gantt chart should be established and revised as the project progresses. This not only informs each team member of deadlines and tasks, but also becomes documentation for the project. The evolution of the project, based upon the evolution of the timeline, is valuable documentation which can be analyzed and reviewed. Conclusions from the study can then be applied to other projects.

Like other research activities, weekly, biweekly or monthly meetings are crucial towards progress and troubleshooting. While initial invention efforts requires much effort for originality, continuing activities require dedication, determination and discipline; creativity permeates all activities, and the focus of work must be redefined as new discoveries are made and milestones are reached.

6.2.5 Innovation Conception

Invention can strike at any time, but there are some activities that can help generate ideas and concepts:

- Brainstorming sessions
- Attending product demonstrations at trade shows
- Walk-throughs of stores
- Perusal of trade magazines and catalogs of existing products
- Talking with colleagues and end-users about problematic products

- Reviewing television shopping networks

These activities show what is already in the market, and what new products are emerging. Insights can be found by identifying trends in new products and areas in which products have not yet addressed.

6.2.5 Patent and Market Research

Once an idea is found, a search for the innovation should be made in existing patents, product catalogs and other resources. If indeed the idea has already been patented or is in practice, the idea may be refined or modified to reflect new features not yet addressed.

In the last year, databases of U.S. Patents have been vastly improved. Two databases providing patent information online warrant particular attention:

- The United States Patent and Trademark Office (USPTO) includes an online database of issues patent abstracts, as well as information and publications on patent laws, international patents and related news. This site is found at `http://www.uspto.gov` .

- An IBM-sponsored site has a database with the abstract, claims and figures of U.S. Patents. Full patents may also be ordered online. The WWW URL address for this site is `http://www.ibm.com/Patents` . An alternative address is `http://patent.womplex.ibm.com` .

Two years ago, in 1995, these databases were only beginning to fill in, and a standard library patent search was necessary. This manual search can be done at the Boston Public Library, site of a depository of patents on microfilm, a subscriber to *The Official Gazette*, and equipped with computer keyword-search databases for patents. However, online resources provide 24-hour remote access to patent information essential to product innovation research, and can significantly shorten research time.

Specific company information can be found at http://www.*companyname*.com, sites sponsored and maintained by companies for purchasing, advertising and other services.

Although not all companies have web sites at this time, firms in increasing numbers are going online.

For marketing and corporate information, the United States Securities and Exchange Commission (SEC) maintains a database of corporate documents made public as required by SEC law. Articles such as annual reports and quarterly reports, changes in stock policies and the like can be found in the Electronic Data Gathering, Analysis and Retrieval (EDGAR) system at `http://www.sec.gov/edgarhp.htm` (not `.html`).

Other market information can be found in numerous sources in major libraries. Specific company listings and industry articles indices can be found in compilations such as:

- Business Periodical Index – index of articles in selected industry areas
- Magazine Index and Newspaper Index – bibliographies of articles on microfiche
- Burrelle's Media Directory – guide to newspapers, magazines, newsletters, radio, television
- U.S. Manufacturers Directory – listings of manufacturers
- Thomas' Register – a "yellow pages" of manufacturers and suppliers of goods
- Findex – a listing of market research reports and surveys for twelve target markets

The above list is by no means comprehensive. Major public libraries and business school libraries, including Dewey Library at MIT, often have extensive resources for collecting market data.

6.2.7 Development, Modeling & Fabrication

For simple consumer products, prototypes and mock-ups can be made "in-house." For machining and other fabrication techniques, the machine shops at MIT discussed in Section 6.1.1.

For more complex products, a virtual model may be the most cost-effective equivalent to a prototype. Since today's computer applications such as Pro/ENGINEER™ and

SDRC I-DEAS™ also perform analysis and manufacturing operations on virtual parts and assemblies, a virtual prototype can be an effective alternative.

Cost of materials and the fabrication of prototypes can be an obstacle for individuals. However, if a sponsor or faculty participant in the department can allocate funds for the product innovation, then prototyping a design can be a justifiable expense. Care must be taken, though, to ensure that the design addresses manufacturing and cost-related issues.

In some cases, the services required by an outside source may be acquired without charge. Machine shops and companies with whom MIT faculty and groups have a working relationship may be willing to donate small contributions to a product innovation project. If available, it is important to follow-up with the company and maintain good relations, including the company in the development acknowledgments.

6.2.8 Finding a Sponsor

Of all the tasks of product innovation research, finding a company sponsor to license or co-develop the ideas is perhaps the most nondeterministic and elusive. Companies receive new product ideas from within the company and from outside, and it is not necessarily easy to gain the attention of a company representative.

Though evaluation methods and policies differ from company to company, there are a few common tasks:

- Product concept contributions should have pending patent status, if not an issued U.S. patent.
- Companies often have a New Products Division or an equivalent. A person in Sales & Marketing may also be the appropriate contact. Find out who is in charge of accepting concepts, and inform them of your intention of submitting an idea.
- Non-disclosure agreements must be signed. The agreement letter can be obtained from the company.

- A letter of introduction should be sent with the signed agreements, a product sheet and samples. Do not expect any item to be returned. Indicate who you are, and the central features of the innovation.
- Follow-up with the company, calling back the company contact after the submission is expected to have arrived, and a week or two later to determine the status of the product evaluation.

If the company expresses interest, they will inform the project team contact person. From that point, a number of alternatives are possible, ranging from continued evaluation of the product internally, to a joint development effort and perhaps a licensing discussion.

This stage of development and marketing can take months or years. The more complete and customizable the design, the better the chances that a company can adopt it into its existing product lines, manufacturing processes and distribution channels. At some point, legal discussion may begin, and representation may be required. However, this is beyond the scope of this thesis and will not be discussed in further detail.

It should be noted that companies and new products divisions are more apt to deal with and consider submissions from professors and thesis teams than from random, less established sources. Hence, the reputation and trust of an educational institution can have facilitate market entry.

6.2.9 Project Presentation & Publication

The presentation of project work is the outreach of the product innovations to others, including those within the project team and to outsiders such as company representatives and sales and marketing contacts. Project achievements can be communicated in various forms, including the following forms:

- Product sheet, brochures, press releases, advertisements
    - Typically one or two pages in length
    - Shows the innovation (mock-up, prototype or product) in photos or drawings

    - Provides specifications, compared to other related products, in graphs, plots or tables
    - Tells why the innovation is special and has value
    - Includes notice of patent status (pending, issued)
    - Includes contact information and address

- Product samples
    - For easily prototyped or produced products
    - Accompanied by product sheet

- Video cassette
    - For products that are kinetic or dynamic in nature
    - Shows product (prototype) in use
    - Compares product concept to related existing products
    - Voice overview of design challenge and product solution
    - Identifies features and specifications
    - Accompanied by product sheet

Presentations, as in seminars and workshops, should be made to the department or division as progress permits. If possible, a combination of the above three forms should be included into a presentation detailing the design problem and the innovation solution.

An electronic form of publication can be made communicating the innovation to interested audiences. A WWW homepage can be established for each project, and the most current information and developments can be posted online. With the latest developments in web development, sound, graphics and video clips can be included.

6.2.10 Project Documentation

Product Innovation Research is no different from other research in that documentation of designs, changes and correspondence should be kept and organized. Project documentation should include:

- Progress reports
- Minutes to, or summaries of, meetings

- Gantt charts or timelines, as they are revised
- Design "notebook" including sketches, drawings, calculations
- Patent references
- Market references
- Accounting figures (cost of materials, expenses)
- Project publications
- Photos of mock-ups, prototypes, products, processes

This documentation serves numerous purposes, including:

- Proof of invention
- Portfolio material
- Teaching aid for other projects
- Contribution to a library of product innovations

These last points, teaching aids and a library of innovations, are central to the idea that each project experience adds to the program as a whole. Interested students can review these case-studies and learn about successes and pitfalls and be prepared for their own project work.

6.3 Publicizing Product Innovation Research

Like the product innovations must be advertised to potential sponsors, Product Innovation Research as a program must be publicized. Attention drawn to the program brings attention to the product innovations developed by the students; hence, to facilitate market adoption of product concepts and to channel industry interest to the education of the innovation researchers, outreach of the research is necessary.

6.3.1 Displays and Showcases

In various hallways of the Department of Mechanical Engineering as well as other departments, display cases illustrate accomplishments of individuals and organizations. Displaying the projects and products resulting from student-led innovation research is intended to accomplish numerous goals:

- Advertise product innovations to visiting companies and potential sponsors
- Recognize students achieving successful product innovations
- Attract prospective students and visiting scholars and lecturers to MIT and the Department of Mechanical Engineering
- Encourage current and future students to pursue innovation
- Inspire students and make them aware of the possibilities of design and invention, career and profession

6.3.2 Online Publications

Given that the Internet and the World Wide Web continues its ubiquity in the marketplace and business world, publishing product innovation online is a logical step towards advertising product designs and the innovation research program itself. The site could be linked to the Institute's and the Department's web pages, and would include the multimedia product sheets, described in Section 6.2.9.

A prototype WWW publication site is currently under development, and contains some of the product concepts of the case-studies of Chapters 4 and 5. It can be found through the PERG homepage at `http://pergatory.mit.edu/links.html` or at the prototype location `http://web.mit.edu/course/2/2.971/www/frames/index.html` The site is listed as part of the Urban Design Corps (UDC) and is currently under construction at the time of writing of this thesis. See Sections 4.1.3, 4.1.4 and 7.2 for more information of the UDC.

6.3.3 Student Portfolios

As the product innovation activities progress, students will have gained skills through developing product concepts. For their benefit, their personal portfolios should contain pages related to these innovation efforts. The same material used in product sheets publications can be used to develop their portfolios. Photos, comparative data and other elements from the innovation documentation are readily transformed into elements of their portfolios. Even if the product concepts fails to enter the marketplace, the education gained by the student will benefit the students by demonstrating to potential employers that the students have experience in real applications of their knowledge and in a broader, useful state for faster transition into the workplace.

6.4 Program Formalization

While product innovation research can be continued in its informal fashion within individual research groups, a larger step towards increasing student involvement is the formalizing of the activities into a departmental program. Formalization can take on various degrees of recognition and implementation, as this section suggests.

6.4.1 Parallel Development in Coursework

The Department of Mechanical Engineering at MIT, in its recent restructuring of the undergraduate curriculum, modified the names, requirements and emphasis of its core courses, and also revised its requirements of senior thesis. Taking the restructuring another step further, a Product Innovation Research Program could be positioned alongside certain courses in such a way that the courses would still teach the desired base material for students not involved with innovation research. For students involved with the Product Innovation Research Program, though, the courses and the innovation research would be catalyzing, synergetic and co-complementary.

For example, the Design and Manufacturing course stream of 2.007, 2.008 and 2.009, are required courses typically taken by undergraduates in their sophomore spring, junior fall or spring, and senior fall semesters, respectively. This two year span of increasing-complexity project-based education is a prime series with which a parallel Product Innovation Research Program could be coordinated. The subject or task integration might include these actions:

- Sophomore year
    - As early as fall term, or as late as the end of 2.007, students choose a field of products, and propose several potential product concepts.
    - Before the end of the course, they perform initial market research and patent searches.

  - Students present their findings to classmates in recitations.
  - Findings are compiled, and students choose a few concepts for their innovation research.

- Junior year
  - As an "enabling" assignment (required but not graded) for innovation program students, juniors submit a feasibility study of their chosen concepts and a task list of research duties and deliverables.
  - Additional market research, and patent searches continue. Students select one concept from their initial few.
  - Design and development of the concept progresses.
  - As part of 2.008, the design and manufacturing lessons are applied to the chosen concepts. A final assignment of 2.008 is to report the progress of the innovation research; specifically, how the processes taught in 2.008 have changed the innovation development.

- Senior year
  - The enabling assignment is to submit the project report and a task list which anticipated 2.009 lessons will address.
  - From the concepts which are partially developed by innovation research students, course projects are selected. Innovation students have their projects "adopted" by course, and course students form development teams to prototype and further develop the innovations.
  - At the conclusion of 2.009, projects revert back to the Product Innovation Research Program, for continued development and marketing by principal researching students.
  - Senior thesis requirements may be satisfied by submission of documentation of the product innovation project.

This parallel implementation of the Product Innovation Research Program could also be extended to include:

- Freshman Seminars
- IAP workshops

- Summer and term-time UROP activities
- Year-round 2.996 elective courses in Mechanical Engineering

Graduate students can take part in these activities by serving as:

- Project managers
- Managers-in-training
- Co-developers in Thesis Teams (as discussed in Section 6.2.2)
- Project Assistants (PAs), similar to Teaching Assistants (TAs) and Research Assistants (RAs)

Faculty members would ideally be instructors in the 2.00X course series and also innovation research team mentors.

6.4.2 Course II-A Option

For those students wanting a different undergraduate education, the Product Innovation Research Program offers them the opportunity to conduct research and take more elective courses than usually advised for the mainstream Course II curriculum. Although the Bachelor of Science degree in Course II-A is an undesignated degree, the ability of the student to select closely-related coursework complements the innovation research.

For example, for students concentrating on biomedical or biomechanical applications and innovations, the Course II-A option would support and encourage cross-departmental course selection in biology and medicine. Business school would also offer relevant coursework for complementary coursework. Since specialization and concentration on these course can occur earlier in the student's undergraduate experience, the innovation research may also commence sooner in the student's years. Requirements and course recommendations for the proposed track in Product Innovation is presented here.

Course II-A Requirements (as set by the Department of Mechanical Engineering)

- Required:

  2.001 Mechanics and Materials I (12 units)
  2.003 Systems Modeling and Dynamics I (12)
  2.005 Thermal-Fluids Engineering I (12)

2.007 Design and Manufacturing I (12)
18.03 Differential Equations (12)

- Three out of five courses required:

  2.002 Mechanics and Materials II (12)
  2.004 System Modeling and Dynamics II (9)
  2.006 Thermal-Fluids Engineering II (12)
  2.008 Design and Manufacturing II (12)
  2.010 Control System Principles (9)

- At least six subjects (60-72 units) from 2A tracks
- At least 48 units of additional, unrestricted electives
- 12 unit Product Innovation thesis project over at least two terms
- General Institute Requirements

Course Recommendations for Product Innovation Track

As product innovation can be conducted on a wide range of product markets, a list of courses applicable towards the Product Innovation Track is provided, a more diverse listing compared to the existing five tracks of Course II-A.

Design project-based:

2.670 Mechanical Engineering Tools (6) [project] (prereq for 2.007)
2.72 Elements of Mechanical Design (12) [project]
2.737 Mechatronics (12) [project]
2.009 The Product Engineering Process (12) [project]
2.739/15.793 Product Design and Development (12H) [project]
2.74 Optimal Product Redesign (9G) [project]
2.744 Product Design (12G) [project]
2.782/HST.524 Design of Medical Devices and Implants (12H) [project]

Analysis Tools and Experimentation:

2.31 Finite Element Analysis in Computer Aided Mechanical Design (12)
18.443 Statistics for Applications (12)
15.069 Experimental Design and Taguchi Methods (6H)

Human Interaction with Designs:

16.400 Human Factors Engineering (12)
MAS.100 Introduction to Media Arts and Sciences (6)
MAS.837 Collaboration Between People, Computers and Things (9H)

Intellectual Property and Entrepreneurship:

2.942 Entrepreneurship (9G SWE) [project]
6.901 Inventions and Patents (9 SWE)
15.375 New Enterprises (9H) [project]

Economics:

14.01 Principles of Microeconomics (12 HASS)

14.02 Principles of Macroeconomics (12 HASS)

Management, Marketing and Policy:

2.96 Management in Engineering (12 SWE)
15.351 Introduction to Technological Innovation Management (9H)
    or 15.352 Management of Technological Innovation (6H)
15.812 Marketing Management (9H)
17.172/22.843 Technology, Productivity and Industrial Competition (12H)

where: (#) = total units; G = primarily graduate course; H = H-level graduate course
SWE = school-wide elective; HASS = Humanities and Social Science credit
[project] = project required

Example course selection:

2.670 Mechanical Engineering Tools (6) [project] (prereq for 2.007)
2.009 The Product Engineering Process (12) [project]
2.72 Elements of Mechanical Design (12) [project]
2.744 Product Design (12G) [project]
2.942 Entrepreneurship (9G SWE) [project]
6.901 Inventions and Patents (9 SWE)
15.351 Introduction to Technological Innovation Management (9H)
2.96 Management in Engineering (12 SWE)
16.400 Human Factors Engineering (12)
MAS.100 Introduction to Media Arts and Sciences (6)
17.172/22.843 Technology, Productivity and Industrial Competition (12H)
+ other electives

6.4.3 Minor in Mechanical Engineering

Students majoring in other departments may consider the Product Innovation Research Program as an ideal way to conduct their studies for a Minor in Mechanical Engineering. As part of their required coursework in Mechanical Engineering, students may take courses dedicated to the Product Innovation Research Program. Depending on the student's goals, they may serve as principal innovators or as supporting co-developers. In either role, the project on which they participate serves as a focus to their coursework for the minor.

6.4.4 Master of Science Degree Research Topics

Upon admission to graduate school, a faculty member may invite students to consider product innovation projects related to the faculty member's field of expertise. The graduate student would then propose and proceed with research and concurrent development on innovations as part of the advisor's research group. A thesis team, as outlined in Section 6.2.2, would then be an option for structuring the advisor-advisee working roles.

Care must be taken, however, to observe the rules and guidelines regarding intellectual property and ownership. As law requires the assigning of certain inventions and designs to the Institute, property rights should be clearly determined and understood before the commencement of innovation research.

6.4.5 Center for Innovation & Product Development Collaboration

As the new Center for Innovation and Product Development continues its launch at MIT, the Product Innovation Research Program can be aligned with its functions. This cooperation serves as an opportunity for the Center's company partners and innovation research students to share resources and product concepts.

One of the more difficult tasks in developing product innovations is finding a "market in" and a company sponsor. Connecting the Product Innovation Program with the Center would provide easier transmission of product ideas from students to companies, and would also facilitate education of students of industry practices.

At the same time, it would not require the absorption of innovation research students into another program. Unlike the New Products Program organization, students could retain their independence and ownership of the innovations, as the invention and concurrent development would be conducted outside of the company setting.

For this implementation option, agreements must be made between the Center's industry partners and a legal proxy for the Product Innovation Research Program.

6.4.6 Department Sponsorship of Product Innovation

As events such as the Lemelson-MIT Student Prize and the $50K Competition continue, the Department of Mechanical Engineering should sponsor a Product Innovation Research Program to motivate, support and encourage student innovators. In addition, this sponsorship would provide for the financial and material resources that are essential in the later stages of product innovation research stages, for prototyping and manufacturing, for example.

One such sponsorship can take the form of Innovation Scholarships from an Innovation Venture Challenge. Interested freshmen would submit a summer UROP proposal on their interests in product innovations. The summer would be spent:

- Investigating product ideas, opportunities and the market
- Outlining what fundamental subjects and courses at MIT are needed for development of their innovations
- Proposing how those courses would contribute to the project, including specific goals and objectives of each course
- Writing a "business plan" outlining the tasks and deliverables for the next three years

At the end of the summer, students submit these "business plans", and winners of the Innovation Venture Challenge receive full three-year scholarships to execute their plans. Project reports are kept current throughout the three years, including reports of contributions and results from each course cited in the plan.

Sponsoring such programs would not only demonstrate true commitment to meeting the changing educational needs of students, but also strengthens the department vision of producing the next leaders in industry and academia. By design, the Product Innovation Research Program encourages creative, talented and entrepreneurial students to learn, innovate, and pursue new ventures.

6.5 Limiting Issues

As mentioned in Section 3.2.2, one of the obstacles of invention and product success is lack of financial resources. Also, as the innovation efforts are being conducted within the university environment, the established university laws of ownership rights must be respected. The two issues should be carefully considered for each project, and steps should be taken to minimize the obstruction of innovation by these concerns.

6.5.1 Budgetary Constraints

Depending on the product, the cost of developing and patenting the invention may not be affordable for the students. Cost of materials and contract manufacturing, for example, may well exceed a student's finances. Patenting can also be expensive – while the application fee is a few hundred dollars, patent attorney fees are generally not affordable for students. If the project is not funded by a group or department fund, the product innovation may stall due to expense. To prevent property right controversy, these outside funds must be clearly given with the agreement that the ownership of the inventions are retained by the student.

6.5.2 Intellectual Property Rights

By law, inventions conceived and developed with university resources under certain conditions are the property of the university. For example, if an invention is discovered while conducting research for a project funded by a government agency, the student cannot claim ownership of the invention. These conditions can be found at the Technology Licensing Office (TLO); various publications and brochures outline the rights of the individual regarding intellectual property.

However, one of the advantages of the Product Innovation Research Program is the minimal controversy over who retains the rights to inventions. Since the students invent on their own, without responsibility or obligation to a particular sponsor-funded research effort, the inventions are more clearly the property of the students. Students may still choose to assign their inventions to the TLO, but is not a requirement.

Chapter 7

Conclusions

Product innovation requires the integration of design, development and marketing of concepts and principles. These tasks involve understanding in both technical and non-technical fields, and the process of bringing an idea to market is best done with a deliberate course of action coordinating those tasks.

This thesis has shown how education of future engineers and designers can incorporate the product innovation process into a university course of study. As a complementary activity to existing activities within the university and school of engineering, product innovation research and discovery can serve multiple functions: catalyzing and enhancing students' education, expanding university-industry cross-pollination and communication, and producing potentially successful new products.

Section 1 summarizes the effects that product innovation has on the continuous educational process from the student, university and industry perspectives. Section 2 summarizes future work that would further the program and its principles.

7.1 Revitalizing Education & Industry

Of primary concern to society is the ability of the university to teach its students in an effective and efficient manner. Especially in the field of engineering and design, where more and more information and best-practices are considered important to the practicing engineer, designer and entrepreneur, a proactive stand in education is required to satisfy student and company demands. The customers of education are not only the students, but the university itself, which depends in part on the success of its graduates, as well as industry, which is responsible for the continuing education of its employees.

7.1.1 Benefits for the Students

Product innovation provides an education in practiced design and wisdom, creating a market pull for knowledge, skills and expertise at the individual student level. Providing each participant with a stake and ownership in the project creates senses of passion and urgency, characteristics which have been shown to drive the project and education in a unique, beneficial fashion.

Students involved with the Product Innovation Research Program gain practical experience in product design, development and marketing. Rather than conducting work within established, controlled and often limited-scope activities of a given course, they investigate and discover knowledge, skills and insights in an environment with few bounds in subject matter and possibilities. This frontier of innovating is crossed by student pioneers with the support of faculty and graduate student guides.

In doing so, innovating students discover a world of cross-disciplinary applications for which there may be no single "correct answer," and gain the opportunity to design and create solutions to the best of their abilities. Not only does this mirror the real world of industry, it also reveals to the students that design in practice requires a solid foundation in engineering theory as well as in non-technical fields such as social science, business and marketing, and law.

The created market-pull or personal demand for knowledge and skills changes the way in which a student interacts with the university and the greater working community. Students learn to identify strengths and weaknesses in their own skills-set, and in trying to reach a successful project objective, they forge ahead and discover on their own. Islands of education can be bridged, connected and thus transformed into useful cornerstones of their experience.

Through a modified form of apprenticeship, the practices required and recommended for innovation and entrepreneurship are passed down from faculty and supervisor champions, to supervising student managers, to the innovative students. As the projects progress and evolve, the students learn firsthand the methods of innovation and of teaching innovation, and thus are better prepared to carry on the principles of education, creativity, invention and development to the next participants.

7.1.2 Opportunities for the University

The university, and MIT in particular, has the opportunity to transform the way in which design education is implemented with its individual students. Product innovation project activities differ in how each student interacts with his or her peers, colleagues, and supervisors, as well as the marketplace and industry. Hence, the university has another medium through which it can prepare its students and expand upon its role in the greater community.

By forming partnerships with industry, and paying particular attention to the individual working relationships between innovation students and company employees in engineering, business and marketing, the university can strengthen its primary role as an educational institution. It may also become an active member in the marketplace through its students and their project efforts during their undergraduate and graduate careers. Similarly, with collaborating companies, through its employees and shared resources, the university can learn about the strengths and capabilities of industry and in turn apply them to its own programs.

As the environment of academia and its place in society continues to be questioned in a competitive social and business world, the ability to function effectively beyond the bubble of educational realm is a key to survival as well as prosperity. MIT, as a leader in engineering and business research and teaching, can take advantage of its position, associations and history to lead the way to passionate, visionary education.

7.1.3 Commitment by Industry

The search for the next new product or improvement is essential for companies and its customers. Hence, product innovation activities in the university should be of considerable interest to these firms. Not only does product innovation introduce new product concepts to the marketplace, but also potential new hires from the students involved in the program.

This product innovation program also presents industry with the opportunity to contribute to the overall educational system, which provides the backbone for those new inventions and industry leaders. Having a stake in the future, by participating with the individuals who will shape and guide that future, is a commitment that companies must realize is in the interests of the community as well as their own.

7.2 Future Work

Similar to the ongoing development of innovation projects themselves, the development of product innovation research and discovery would benefit from further implementation and evolution. In the levels of the project, program, the university system and beyond, product innovation can play a more significant role in improving education and preparation.

7.2.1 Continuing Project Development

The projects of the case-studies presented in Chapter 4 continue to develop. Some projects, such as StoneMasters™, Leaf Slayer™, MassagaSoap™ and TetraSponge™, remain within the university environment to catalyze creativity and education. Other projects, such as the UniFlex Riser™ and Cubbeez™, have progressed beyond the university and serve as ongoing activities for the original and additional participants. In addition, the growing network of companies and individuals participating in these projects continue to grow. The working relationships of these parties facilitate the introduction of new projects and products.

7.2.2 Program Development

In order to further implement product innovation activities at MIT, the activities can be incorporated into the department though various ways. Coursework can be aligned or directed towards the tasks and issues required by product development by the individual inventor and entrepreneur. Course curriculum requirements and degree work may include more emphasis on product innovation and concurrent development. Additional faculty, including current professors as well as new faculty specifically qualified to champion product innovation in the university, are important for the success of the product innovation program. Students must also take active roles in their education by driving their innovation and creation efforts.

7.2.3 Expanding to Other Universities

With the lead from MIT and the Department of Mechanical Engineering, other universities can apply the principles of the Product Innovation Research Program to suit their particular environments. Other universities already encouraging student entrepreneurism in their own ways can incorporate the principles of student ownership, faculty-student mentoring and supported independence to enhance students' educational experiences and career preparation. Care must be taken to respect the differences in university systems and cultures; however, the basic tenets of the Product Innovation Research Program can be retained without conflict.

7.2.4 Other Product Innovation Programs

Just as some of the case-study product concepts and projects eventually move outside of the university environment, so does the product innovation vision. The principles of catalyzing education, supported independence and product design, development and marketing by youth can be applied by organizations in non-academic environments.

The Urban Design Corps (UDC) is one such organization, focused on starting companies guided towards providing careers and resources for minorities and underprivileged people. It also provides an opportunity for successful members of communities to assist in the economic revival of the larger community through empowering disadvantaged but otherwise capable contributors. From returns on successful products launched by companies of the UDC, additional enterprises can be founded, furthering the revitalization of communities through product innovation and artistic pursuits.

Other implementations may include industry-school partnerships at the K-12 level. Demonstrating the principles of product innovation research and discovery at an earlier age can provide an impetus for youth to pursue their creative ideas in a directed, supported fashion. By the time they reach either college or the working world, they will have insights and experience in problem solving and other valuable working skills that can be applied to their chosen fields.

Appendix

Appendix A

List of background patents used for patent application.

Appendix B

U.S. Patent application (without claims) "Modular storage system, components, accessories, and applications to structural systems and toy construction sets and the like" by A. H. Slocum & C. M. Ho, filed February 1996.

Appendix C

Product sheet for Cubbeez™ Modular Storage Systems.

Appendix A

An extensive search of U.S. Patents was conducted for the patent application "Modular storage system, components, accessories, and applications to structural systems and toy construction sets and the like" by A. H. Slocum & C. M. Ho, filed February 1996. These patents are listed here, in chronological order of patent issue.

Patent #	Date issued	Title
D179688	12-Feb-57	Set of toy building blocks or similar article
3 005 282	24-Oct-61	Toy building brick
3 024 254	15-May-62	Toy building sets and building block
3 162 973	29-Dec-64	Toy building element
3 485 433	23-Dec-69	Knockdown box or crate
3 597 875	10-Aug-71	Toy building set
3 613 931	19-Oct-71	Collapsible crate or box
3 932 976	20-Jan-76	Prefabricated structural panels
3 942 290	9-Mar-76	Integrated building construction
3 958 388	25-May-76	Modular building structures
3 964 809	22-Jun-76	Modular cabinet structure
3 964 810	22-Jun-76	Modular shelf and cabinet system
3 965 826	29-Jun-76	Shelving structure
3 986 316	19-Oct-76	Joint assembly
3 991 533	16-Nov-76	Louver assembly
3 991 535	16-Nov-76	Pressed-in dovetail type joint
3 999 818	28-Dec-76	Modular storage system
4 044 910	30-Aug-77	Collapsible crate
4 102 275	25-Jul-78	Adjustable modular bookcase
4 233 878	18-Nov-80	Barb and method of making same
4 238 044	9-Dec-80	Collapsible plastic crate for display and transport of perishable commodities
4 339 047	13-Jul-82	Collapsible storage and transport crate capable to be stacked
4 343 400	10-Aug-82	Container crate that can be stacked or nested
D273338	3-Apr-84	Crate
D273523-526	17-Apr-84	Stackable plastic crate
D277797-800	26-Feb-85	Tote box; Stackable crate; Holder for utensils; Stackable crate
4 528 916	16-Jul-85	Plural box construction
D279915	30-Jul-85	Toy construction piece
4 542 702	24-Sep-85	Joint element to support and secure shelves in a bookcase or stand, and a set of shelves employing said joint element to support and secure the shelves between the uprights
4 545 698	8-Oct-85	Connector for detachable connection of components of furniture or the like at right angles to each other
4 571 200	18-Feb-86	Modular toy building set
4 574 550	11-Mar-86	Building wall and insulation assembly
4 585 422	29-Apr-86	Toy construction kit
4 611 879	16-Sep-86	Modular block and electrical interface assemblies employing same
4 619 371	28-Oct-86	Three-sided, stackable material handling crate
4 628 653	16-Dec-86	Insulated concrete panel
4 629 161	27-Jan-87	Shelving device
4 688 362	25-Aug-87	Set of modular building construction elements

4 789 075	6-Dec-88	Collapsible plastic crate
4 817 356	4-Apr-89	Construction systems and elements thereof
4 820 077	11-Apr-89	Framing bar connector for a frame
4 822 314	18-Apr-89	Interlocking container and toy block sets
4 822 315	18-Apr-89	Toy construction apparatus
4 825 529	2-May-89	Framing bar connecting method
4 884 378	5-Dec-89	Structural assembly for producing walls
4 889 254	26-Dec-89	Boxes for packaging or storage of various objects
4 895 548	23-Jan-90	Collapsible construction set
4 911 303	27-Mar-90	Stackable rectangular crate, especially for bottles
4 917 255	17-Apr-90	Collapsible container
4 922 678	8-May-90	Structural assembly for producing interconnecting structures
4 923 079	8-May-90	Collapsible container
4 926 758	22-May-90	Playtray with hinged legs
4 934 765	19-Jun-90	Furniture which may be assembled without tools and corner-hinge therefor
4 934 858	19-Jun-90	Fastening device for support structures
4 940 147	10-Jul-90	Visual compact disk wall rack
4 940 149	10-Jul-90	Building assembly system
4 940 150	10-Jul-90	Modular storage rack
4 940 155	10-Jul-90	Collapsible container
4 961 295	9-Oct-90	Metal slat and wall system utilizing same
4 962 805	16-Oct-90	Furniture connector
4 964 349	23-Oct-90	Load carrying platforms
4 964 350	23-Oct-90	Plastic frame system having triangular support post
5 018 628	28-May-91	Working surface
5 038 534	13-Aug-91	Unitary panel module and connector
5 038 539	13-Aug-91	Work space management system
5 061 219	29-Oct-91	Construction toy
5 074 093	24-Dec-91	Overlapping architectural tiles
5 094 356	10-Mar-92	Knock down bulk container
5 117 989	2-Jun-92	Shelf storage furniture apparatus
5 137 239	11-Aug-92	Peg board hook with barbed protrusion
5 137 486	11-Aug-92	Multi-planar connector element for construction toy
5 158 187	27-Oct-92	Tray of shelf-like structure
5 185 982	16-Feb-93	Corner joint for modular assemblies
5 195 642	23-Mar-93	Display or storage rack
5 199 577	6-Apr-93	File rack
D336320	8-Jun-93	Toy building block
5 250 000	5-Oct-93	Play kit with detachable play surface
D343427	18-Jan-94	Toy building block
5 350 331	27-Sep-94	Construction toy system
5 394 658	7-Mar-95	Free standing modular furniture and wall system
5 397 087	14-Mar-95	Universal mount for shelving system
5 398 834	21-Mar-95	Container, in particular, container for vegetables made from plastic material and having foldable side walls
5 398 835	21-Mar-95	Collapsible material handling container having improved corner interlock
5 399 043	21-Mar-95	Joint connection-system for planar or three-dimensional trusses
5 399 044	21-Mar-95	Rigid intersection connection
5 433 053	18-Jul-95	Barbed tee fastener
5 439 309	8-Aug-95	Joint coupling

Appendix B

Patent application (without claims) "Modular storage system, components, accessories, and applications to structural systems and toy construction sets and the like" by A. H. Slocum & C. M. Ho, filed February 1996.

The full write-up, without claims, and accompanying figures follow the abstract.

ABSTRACT

The invention is concerned with the formation of modular units from individual plate-like elements and other elements with special interlocking joints at their ends that allow them to form cubes that can be grouped together to form storage "cubbies" and modular structural systems and toy construction sets and the like. In one embodiment, the plates are formed with one end having studs on a 45 degree angled surface, and the other end having receptacles or openings such as sockets on a 45 degree angled surface for interlocking with a second mating plate like the first, but in which the studs and sockets are interchanged, allowing a cube to be formed by two of each type of plate, with the use of studs and sockets on the surfaces allowing two or more such cubes to stick together.

In another embodiment, the cube is made from four identical plates, as by an extrusion process, where one end of a plate contains double male features, such as barb arrows, and the other end contains double corresponding female features that mate with the male features from other plates, whereby the male and female features allow the ends of the plates to slide into each other like a dovetail to form a cube, and with adjoining cubes sharing surfaces. Other variations are also disclosed.

MODULAR STORAGE SYSTEM, COMPONENTS, ACCESSORIES, AND APPLICATIONS TO STRUCTURAL SYSTEMS AND TOY CONSTRUCTION SETS AND THE LIKE

The present invention relates to modular interlocking construction structures, being more particularly directed to the creating of modular structures from plates and attaching components provided with end features that allow them to be joined together to form sturdy cubic-type and other structures, with the unit structures themselves being adapted to interlock to form arrays of cube-like and other structures that can be used as customizable modular systems for storage, shelter and other applications, including, also, toy construction sets and the like.

BACKGROUND

There are a great many different types of storage devices on the market embracing a variety of different techniques and designs for storage volumes, containers, shelving systems and the means for assembling them. There are also numerous types of construction sets, building blocks and interlocking accessories useful as toys. There are also varied designs for joining and attaching components and structures together for such storage systems, wall shelving, toys, and in the shelter fabrication and assembly industry, among others. The patent categories related to this invention have been identified as: collapsible crates, open-end boxes and containers; modular shelving, display racks, and storage devices; housing and building materials, larger structures, paneling and tiles; workspace management systems; toy construction sets and accessories; joints and interlocking features.

The category of crates and containers includes numerous prior inventions for desired ornamental appearances and for functions of stackable and often collapsible, knock-down, and foldable types of containers similar, for example, to the common milk crate and the like. U.S. Patents Nos. D273,338; D273,523 through D273,526; D277,797 through D277,800; 4,619,371; and 4,911,303, as illustrations, show various designs of such single-piece stackable crates. Often these crate designs include small tabs or other features that align the crates when situated side-by-side or with one on top of another (typical vertical stacking). Actual use of these crates in non-vertical stacking situations, however, demonstrates that the crates are not well-connected to one another and are therefore susceptible to separation and disorganization. A collapsible container, moreover, is often desired for its more-compact shape when not being used to transport or store objects or materials. In U.S. Patent No. 3,485,433, for example, the need for edge strength in a knockdown box is recognized and the structure accordingly includes a frame of stronger material in the fold-over wall panels of the container. In U.S. Patent No. 3,613,931, the walls of the container are held together by simple grooves and connecting strips. These two concepts allow for the compact stacking of the wall panels when not in use; but when in use, however, the joints are not strong enough to resist shear loads and side loads that occur when the containers are oriented with the "top" opening disposed sideways. While improvements in these structural deficiencies have been addressed, there still exist in prior single-piece crates and containers, as well as in the more robust, often plastic and ribbed, designs of, for example, U.S. Patents Nos. 3,485,433; 3,613,931; 4,044,910; 4,238,044; 4339047; 4,343,400; 4,789,075; 4,917,255; 4,923,079; 4,940,155; 4,964,349; 5,094,356; 5,398,834; and 5,398,835. Such prior collapsible container designs have numerous varied mating features; some even include springs and small parts that must be assembled into the container wall panels. These complicated features and numerous parts, however, add to the cost of the products without actually significantly improving structural quality when stacked with openings oriented sideways. The panels themselves, moreover, are different within each container set, with sides and bottoms being significantly different from one another, thereby increasing the number of components that must be manufactured, distributed, stored and inventoried. Also, when stacking these containers in arrays, container walls are redundant – neighboring container units can share common walls, but these designs do not provide a means of sharing walls in semi-permanent applications such as storage and object organization and similar useages.

In the field of modular shelving, display racks, and storage devices, there are three general classes of such devices: single-piece storage units that interlock; free-standing modular shelving-type designs; and shelving designs for wall-mounted assemblies.

The prior single-piece container type designs in this grouping include means for more rigid attachment to neighboring containers, as opposed to the alignment features of the crates of the previously-described section which provide alignment and very little resistance to dismounting. Systems of this type include the structures of, for example, U.S. Patents Nos. 3,964,809; 3,999,818; 4,528,916; and 4,389,254. The design of U.S. Patent No. 3,964,809 features a locking tab and pin component on the inside of one of the unit cabinet walls that interlocks with the component on another stacked cabinet unit. While this secures a plurality of container units together in a more rigid fashion, the additional locking elements to each cabinet unit raises part count and increases the cost of such units. U.S. Patent No. 3,999,818 shows a storage module with interlocking dovetail projections and grooves that are integral to each unit and that allow slide-motion interlocking at any of the five walls of the module, the sixth side being open. These grooves and projections, however, are numerous and leave the outer walls of any unattached unit with a non-flat surface. The walls between attached units, moreover, are redundant. For applications where a storage configuration is not often changed, this redundancy costs the user some storage space and money. U.S. Patent No. 4,889,254 is a similar design for interlocking boxes in which the unit boxes have dovetail features on the four sides so that a two-dimensional array of container units can be formed. In U.S. Patent No. 5,195,642, as a further example, a display and storage rack is disclosed for cassettes and like shapes and that is comprised of single storage units that can be attached to other identical units to form a larger structure. The design of previously cited U.S. Patent No. 4,528,916, as still another illustration, relates to the customization of safety deposit boxes, and provides a means of using a single, shared partition wall between adjacent safety deposit box volumes that can be removed only when the two doors of the adjacent boxes have been opened. The width of the boxes, however, is not changeable, nor can the array of boxes be modified to be larger or smaller than the outside frame structure, so that all modifications to the array must occur inside that given frame.

Prior art shelving and structure designs that are of the modular, free-standing types are also numerous. Examples are described in U.S. Patents Nos. 3,964,810; 3,986,316; 4,934,858; 4,940,149; 4,940,150; 4,964,150; 5,158,187; involving separate shelf units and post units. By combining shelf units and the requisite number of post units, a customizable shelf structure of any integral dimensions can be obtained. In some of these designs, the shelf units are shared by adjacent storage volumes, and in some designs, the post units are also shared by adjacent shelf units. Thus, these structures are more efficient in terms of element usage as they do not result in redundant members. Such designs either involve additional parts, like the several parts that make up a post unit in U.S. Patent No. 3,986,316 or the multiple components of the shelf unit of U.S. Patent No. 4,964,350, for example, or the attachment between the posts and shelf units are susceptible to separation by side, shear or upward forces. Another approach is provided in U.S. Patent No. 5,185,982, using a corner joint of vertical and horizontal rail members of a modular assembly of an open frame. But such a design does not allow change in array size of a given frame without replacing original rail members with longer or shorter rail members, resulting in several unused original members, which is deemed undesirable and wasteful.

Previously proposed wall-mounted shelving designs are also numerous and extensive. U.S. Patent No. 3,965,826 is an example of prior wall-mounted shelving comprised of rails that are mounted to a wall, cantilever brackets that fit into the rails, and shelf elements that are placed on the brackets. While this type of shelving is popular and widely used, it requires the mounting of rails to walls, which does not allow for simple removal or lateral relocation of the shelving. For those users who do not have the skills or tools safely to mount the brackets to the wall, moreover, this design is not desirable. These wall-mounted designs, furthermore, do not provide for integrated divisions along a shelf, so additional bookends and the like must be used. Such a wall-mounted system is also often difficult to make aesthetically attractive in its setting, since the rails and brackets are quite visible.

Turning now to the art embracing modular housing and building materials, large structures and paneling, the construction industry often uses modular materials that allow for the construction of structures involving joined modular components such as wall elements, tiles and panels. For example, U.S. Patent No. 3,942,290 discloses interlocking connectors to attach structural components together. This connector features a multiple dovetail cross-section that slides into the attaching structural unit along the edge of that unit and thus prevents detachment in the orthogonal direction. As will later be more fully explained, for the purposes of the present invention such multiple dovetail joint configurations are not well suited to connect multiple components at a single joint since the multiple dovetail features make the connector rather large at each joint. U.S. Patent No. 3,958,388 also shows the use of a dovetail clamp to connect adjacent construction members, but in this use, where elements are pushed together to mate, adequate pulling forces in the opposite direction or twisting can cause the joint to fail. When the dovetail joint is used in a sliding fashion, as is disclosed in U.S. Patent Nos. 3,942,290; 4,884,378; and 4,688,362, for example, and as is typically done in wood-working joints, an assembled structure has stronger joints; but when using a plastic or rubbery material that can undergo elastic or plastic deformation, a dovetail protrusion can pull out of the dovetail groove. As still a further approach, U.S. Patent No. 4,688,362 discloses a basic set of modules that can form end-to-end, T-, L- or cross-joints without using end-to-end, T-, L- or cross-connectors. The end features have dovetail or like coupling-shaped protrusions and grooves in such a fashion that the elements of the basic set of modular parts can form walls without additional connectors or parts. U.S. Patents Nos. 4,817,356 and 4,922,678 are further illustrations that describe prior sets of structural elements having mating features to assemble the structures.

U.S. Patents Nos. 3,932,976 and 5,074,093 are exemplary of prior techniques involving interlocking tiles and panels. The joints disclosed in the patents, however, are meant for low-load applications and are thus not well-suited for the hereinafter described applications of the present invention.

In still another field, that of workspace management systems, the organization of the workplace often involves the separation of space into personal or smaller workspaces. Illustrative approaches to suitable structures are shown in U.S. Patents Nos. 5,038,534; 5,038,539 and 5,394,658, all disclosing designs describing the numerous modules and pieces involved in assembling customizable workspace management systems. The joints between modules, however, do not scale well for the later-described applications intended by the present invention; on the other hand, the present invention discloses designs of joints that can well be applied to the workspace management system designs.

Discussing, now, the field of toy construction sets and accessories, there exist on the market many popular and successful toy construction sets which comprise building blocks, attaching elements and joints in many variations. These include, for example, the current designs known as Lego™, Duplo™, and K'Nex™. U.S. Patents Nos. 3,005,282; 3,162,973; 3,597,875; 4,571,200; 4,585,422; 4,895,548; 5,061,219; 5,137,486 and 5,350,331; describe some of the designs for elements of these and other toy systems. In each of these designs, the assembly of interlocking pieces is made simple enough for children to assemble, while providing adequate structural properties to withstand loads and forces typical of the playing environment. For larger loads and twisting forces, however, the joints may not be adequate.

There also exist a great number of accessories for such play sets. Examples are shown in U.S. Patent No. 4,822,314 involving a container on which construction blocks may be attached and in which the same blocks may be stored. Similarly, U.S. Patent No. 5,250,000 discloses a play kit with a detachable play surface, a carrying case with a playing surface on which building blocks may be attached and in which the blocks may be stored. In U.S. Patent No. 4,926,758, a play tray with hinged legs is provided. In each of these accessory designs, the case or container serves a second purpose in addition to its play value. These designs, however, do not lend themselves to the building of larger-scale structural arrays with play and storage value by elements that are themselves modular building entities.

In addition to the joining techniques and interlocking features disclosed in the patents discussed above, there are many other prior joint designs that have proposed, such as those disclosed, for example, in U.S. Patents Nos. 3,991,535; 4,233,878;

4,542,702; 4,545,698; 4,629,161; 4,820,077; 4,825,529; 4,962,805; 5,018,628; 5,137,239; 5,397,087; 5,399,043; 5,399,044; 5,433,053; and 5,439,309.

Despite all these varied approaches over the years in the many fields above-described, there still remains the need and the desire for providing improved modular elements, components and accessories for economical, attractive, practical and simple customizable modular storage systems, and also for toy sets, workspace management systems, and housing and building applications, by employing novel and robust designs that are easy to make and assemble and that eliminate the various disadvantages of prior art techniques as before described

Even in the light of all the designs that have been previously developed, indeed, the most popular and widely-used design for modular storage is still that of the common "milk crate", or a formed cubicle storage container. This is due to the fact that it is inexpensive and widely available; however, it is also unstable when stacked with open ends horizontal for loading with objects unless one takes the time to bolt or affix the crates together. In the end, however, they still look like milk crates, and they are bulky to ship, and they take up a large amount of shelf space in stores and inventories. The wall thickness, moreover, is not sufficient to support substantial loads such as books. Furthermore, because they must sell for little money to attract buyers, the return on investment for a retailer with limited shelf space or stockroom space is very low. If, indeed, one needs to assemble an array of 20 milk crates in a home or office to form a wall unit this is most awkward.

This has led to the development of the present invention that, in one application, provides what might be characterized as "take-apart milk crates". Such novel and structurally-sound design of modular storage units and accessories also leads to greater applications of these storage systems, with the designs, detailed features, and means of assembly readily scaleable for other applications as well, such as workspace management systems, modular housing construction, and toy construction systems among others.

OBJECTS OF INVENTION

An object of this invention, accordingly, is to provide new and improved designs for modular elements that can be easily assembled to form aesthetic, strong, and functional storage cubes and that can themselves be assembled into an array of storage cubes for storage of odds and ends, clothes, books, and other "cubby" functions, and the like, and without the previously described limitations and disadvantages of prior structures.

A further object of the invention is to provide a novel design for attainment of the primary objective through the use of the Lego™-type concept that makes the four sides of the cube from plates formed with studs and mating sockets, so the cubes can also serve as building units to allow the storage function to be combined with play value.

Another object is to provide an improved design for attainment of the primary objective through the use of a simple cross-section that can form an interlocking joint of very high strength that essentially enables one to form a rigid cube from simple extruded plastic or metal plate-type shapes with special interlocking ends.

An additional object of this invention is to provide supplemental designs for the interlocking extrudable geometries that allow for add-on accessories, such as drawers, dividers and paneling, to the storage structures to provide multi-axis functions and customizable modular systems in addition to the original storage utility.

A further object of this invention is to provide designs of structures and joints that are also useful in both smaller and larger applications, ranging from small-object containment and toy building block systems, to human workspace management and shelter fabrication and the like.

SUMMARY

In summary, the invention, from one of its broader aspects, embraces structural components for assembly into interlocking modular cube-type structures, in turn, interlockable with other similar cube-type structures to form horizontal and/or vertical arrays of cubes, the components having, in combination, substantially planar plates each having movable male protrusions and female openings for receiving the same and disposed in plate end surfaces having at least portions extending at an angle to the plane of the plates

More particularly, the invention is concerned with the formation of modular units from individual plate-like elements and other elements with special interlocking joints at their ends that allow them to form cubes that can be grouped together to form storage "cubbies" and modular structural systems.

In a first embodiment, the plates are formed, for example, by injection molding to have Lego™-type male protrusions (studs) and female openings (sockets) whereby one type of plate has studs on the inside surface and sockets on the outside surface and one end with studs on a 45 degree angled surface, and the other end has sockets on a 45 degree angled surface, and a second mating plate like the first where the studs and sockets are interchanged. This allows a cube to be formed by two of each type of plate; and the use of studs and sockets on the surfaces allows two or more such cubes to stick together, because the studs mate with the sockets, and can also form connections with flat Lego™-type plates with studs and sockets.

In a second embodiment, the cube is made from four identical plates, preferably made from a extrusion process, where one end of a plate contains double male elements or features, such as substantially circles or arrows or similar shapes, and the other end contains double female elements or features that mate with the male features from other plates, whereby the male and female features allow the ends of the plates to slide into each other like a dovetail to form a cube. Adjoining cubes therefore share surfaces, such that to add a cube to an existing array would take at most three more plates.

In a third embodiment, the cube is made from four identical plates as in the second embodiment, but where the ends of the plates are axisymmetric, each end having one male and one female feature, oriented such that a rotation of 180 degrees results in the identical configuration. These plates are also preferably made with an extrusion process, and the plate ends are also slid into each other along the axis of the joint. Adjoining cubes, and also structures with angles other than 90 degrees between plate members, share surfaces.

A fourth embodiment involves a cube plate design where the plate elements have symmetric single male or female features, and a center joint piece with the opposite gender feature. Each cube array joint consists of one core piece, and the walls of the cube array consist of the plate elements. Adjoining cubes share these plate surfaces as well.

A fifth set of embodiments regards the decoupling of the wall component and the end feature components. A user of the elements can customize the modular system by choosing the desired type, material and size of wall element and then combining it with the end joining elements using any of the joint designs of previous embodiments. The cube array is then equivalent to the embodiments described, but allow more user-customization.

A sixth embodiment is a wall truss design which maintains the characteristics of the modular storage concepts above but which also adds functionality to the storage system or structural system with the accessories that can be added to systems by engaging with the specially designed truss cross-section.

In each of the above second through sixth embodiments, when the mating features are configured as a barbed protrusion and a barbed socket, the interlocking of the barb and the socket provides substantially increased strength over non-barbed features.

Further embodiments illustrate types of accessories that can be added to storage or structural systems employing the plate embodiment design and the wall truss designs.

Other embodiments describe tools for material customization and installation, and such as preferred and best mode embodiments are hereinafter more fully described.

DESCRIPTION OF THE DRAWINGS

The invention will now be described with reference to the accompanying drawings in which:

Fig. 1 shows a prior art conventional Lego™-type plate element with studs on one side and the mating socketed surface on the other side;

Fig. 2 shows a plate element designed in accordance with the invention with 45 degree inclined ends and where one end has studs on the inside surface and sockets on the outside surface and the other end has the opposite, and the broad width of the plate has studs on one side and sockets on the other side;

Fig. 3 shows a plate element like that of Fig. 2, but the positions of studs and sockets are reversed;

Fig. 4 shows a cube made from the interlocking plates of Fig. 2 and Fig. 3;

Fig. 5 shows the detail of the joint formed by the plates in Fig. 4, and the use of a plate element from Fig. 1 used to connect two cubes together;

Fig. 6 shows an array of cubes put together to form a bank of "cubbies" for storage;

Fig. 7 shows a stud and socket plate element like that of Fig. 2, but with a different type of 45 degree end that is simpler to form, though not as strong;

Fig. 8 shows the mating plate element to the plate element of Fig. 7;

Fig. 9 shows a cube formed by the plate elements of Fig. 7 and Fig. 8;

Fig. 10 shows a plate element like that of Fig. 7 but with an additional stud and socket orthogonal to the end studs and sockets;

Fig. 11 shows the mating plate element to that of Fig. 10;

Fig. 12 shows a cube formed by elements of Figs. 10 and 11 and two-stud and two-socket plate elements currently available from the Lego Company;

Fig. 13 shows a structure of two "cubbies" formed by the set of elements of Fig. 12;

Fig. 14 shows a stud and socket plate element like that of Fig. 2, but with two-pronged ends with the prongs diverging at + and -45 degrees to the plane of the plate, that enable an array of cubes to be formed that share walls to reduce cost;

Fig. 15 shows the mating plate to that of Fig. 14;

Fig. 16 shows an array of cubes with shared interior plates and exterior plates formed by the plates elements of Fig. 14 and 15, and Figs. 2 and 3 respectively;

Fig. 17 shows an extruded plate element with two round male dumbbell-like prongs on one end and a double mating pairs of round female receptacles on the other end, such that four of these identical elements form a sturdy cube;

Fig. 18 shows an extruded female end cap;

Fig. 19 shows an extruded male end cap;

Fig. 20 shows an array of cubes formed from the elements of Figs. 17, 18 and 19;

Fig. 21 shows an extruded plate element with a pair of arrow-shaped prongs on one end and a double mating female form on the other end, such that when four such plates are slid into each other to form a cube, the male arrows form self locking joints with the female forms that are virtually impossible to pry apart, thereby forming an extremely sturdy cube structure;

Fig. 22 shows a female mating arrowhead form end cap;

Fig. 23 shows a male arrowhead form end cap;

Fig. 24 shows a cube made from the elements of Figs. 21, 22 and 23;

Fig. 25 shows the detail of the joint formed by plate elements of Fig. 21;

Fig. 26 shows how the plate of Fig. 21 may be extruded to have a socketed surface that would mate with a plate with angled ribs to form a very strong plate truss that greatly increases the buckling resistance and load capacity of the system;

Fig. 27 shows a variation on the barbed arrow and barbed slot theme, where the part is axisymmetric;

Fig. 28 shows the type of even stronger interlocking joint that is obtained with the axisymmetric element of Fig. 27;

Fig. 29 shows the end-cap element needed to complete the joint at a free-edge;

Fig. 30 shows a portion of a system that has been assembled to provide modular storage using the axisymmetric elements;

Fig. 31 shows a cube that has been assembled using axisymmetric elements where the plate regions between the ends is formed, e.g., extruded, as a truss to maximize strength and minimize weight (cost);

Fig. 32 shows another asymmetric element like that of Fig. 27 but with different barb and barb mate angles that allow for 45° angles between joining elements;

Fig. 33 shows a close-up of the end of the axisymmetric element of Fig. 32 featuring the same basic features as that of Fig. 27;

Fig. 34 shows a terminating element that is the same as the wall element of Fig. 32 but without the wall plate component;

Fig. 35 shows a longer version of the axisymmetric element of Fig. 32 that may be used to connect joints having 45° between joint elements;

Fig. 36 shows a central core element with a through hole at its center to be used to increase the joint strength of a 45° axisymmetric structure;

Fig. 37 shows a close-up of a joint comprising of the axisymmetric elements of Figs. 32 and 35 and a core center piece of Fig. 36;

Fig. 38 shows a side piece equivalent to three consecutively joined terminator pieces of Fig. 34;

Fig. 39 shows how two side pieces and a core element can join two axisymmetric elements at a 180° angle;

Fig. 40 shows a corner piece equivalent to five connected terminator end pieces;

Fig. 41 shows how a corner piece can be combined with the elements of Figs. 32, 34 and 36 to form a sturdy corner joint;

Fig. 42 shows a structure of 45° element joints using the components illustrated in Figs. 32, 34, 35, 36, 38 and 40;

Fig. 43 shows how the basic concept of the barbed joint can be used to form other joints, where in this case, the plates that make up the sides will all have barbed slots at their ends, and the joint is made from a four-barbed cross;

Fig. 44 shows the inverse, where the joints are all made from a cross of eight female barb sockets, and the side plates would all have barbs on their ends, such that the joint can support orthogonal plates, or 45 degree racking-resistance plates;

Fig. 45 shows how a plate with barbed ends can have a solid cross-section, thereby minimizing extrusion die complexity;

Fig. 46 shows how a plate with barbed ends can be made to have a truss section between the barbs to minimize weight and maximize strength;

Fig. 47 shows a connecting piece that can be used to connect barbed elements at 180° instead of using the multiple-barb-mated cross of Fig. 44;

Fig. 48 shows two barbed elements joined with a connection piece of Fig. 47;

Fig. 49 shows a large unit assembled from the joint and plate units of Figs. 34 and 45 respectively;

Fig. 50 shows an end clip having the barb features of that of Fig. 45 and a toothed jaw replacing the wall component to allow for the attachment of a separate wall or board component element;

Fig. 51 shows the end clip engaged with a wall component element, with the jaw teeth embedded into the wall surface to provide a stronger gripping and attaching strength;

Fig. 52 shows a joint made up of the end clips of Fig. 50 with attached wall component elements in the clip jaws;

Fig. 53 shows a portion of a structure made up of the elements of Figs. 44 and 50 with wall components attached;

Fig. 54 shows another end clip with jaw teeth but with an axisymmetric barb end;

Fig. 55 shows the axisymmetric end clip with a wall component engaged with the jaw teeth;

Fig. 56 shows a joint made up of four axisymmetric end clips with wall components attached;

Fig. 57 shows how a structure can have storage-"cubbies" of various dimensions by using wall elements of different lengths;

Fig. 58a shows a bridge-type storage array;

Fig. 58b shows a different structure using the same elements as used in Fig. 58a;

Fig. 59a shows how flat-head screws can be added to an end clip into a wall component to provide even more attachment strength;

Fig. 59b shows how non-flathead screws having a flat head underside, such as panhead or roundhead screws, can also more permanently attach an end clip to a wall component element;

Fig. 60 shows an end clip with less-protrusive teeth of the jaw to provide more surface area and alignment for an inserted wall component element, which would be desirable when using adhesives to mate the clip to the wall;

Fig. 61 shows how the joint end of the clip can be kept the same while the jaw gap can be made in varying sizes to accommodate wall components of different thicknesses;

Fig. 62 shows how end clips can be attached to any edge of a wall component with any angle between possible attachment edges;

Fig. 63 shows another variation of jaw features in an end clip, with this clip having non-protruding barbs to maintain a constant open gap in the jaw;

Fig. 64 shows a trussed wall element having mating barb features that would interface with the end clip barbed jaw of Fig. 63;

Fig. 65 shows how a barbed truss wall of Fig. 64 mates with end clip of Fig. 63;

Fig. 66 shows how a different end configuration can be used in the non-protruding barbed jaw end clip;

Fig. 67 shows a completed extension joint made up of end clips of Fig. 63 and terminator end elements like that of Fig. 29;

Fig. 68 shows a single connection piece that is equivalent to the joint group of Fig. 67 but stronger because it is one piece;

Fig. 69a shows a longer wall construction made of wall components in end clip elements and connection elements of Figs. 63 and 68;

Fig. 69b shows how the elements of Figs. 63, 64 and 68 can form a stronger wall extension structure;

Fig. 70 shows a corner joint element equivalent to two interlocked end clips of Fig. 63;

Fig. 71 shows a T-joint and a cross-joint using the corner element of Fig. 70;

Fig. 72 shows a wider end clip like that of Fig. 63 alongside two thickness adapters;

Fig. 73 shows how the thickness adapters of Fig. 72 interface with the end clip of Fig. 72 and inserted wall elements;

Fig. 74a shows an axisymmetric-end element having an axisymmetric truss geometry;

Fig. 74b shows an axisymmetric-end element having symmetric truss geometry;

Fig. 75 shows dimensions defining the features of the axisymmetric truss of Fig. 74a;

Fig. 76 shows the thin wall thicknesses on either side of a triangular truss hole;

Fig. 77 shows how a rounded rhomboidal center plug can fit into either orientation of a truss hole;

Fig. 78 shows how a panel with numerous rhomboidal plugs can be rotated 180° and still fit the same truss holes if the truss is properly designed;

Fig. 79 shows a different, smaller corner type of plug on a panel that can also fit in the truss cross-section when rotated 180°;

Fig. 80 shows details of the smaller corner plug geometry;

Fig. 81 shows a V-shaped plugged panel that is constrained when engaged with two parallel truss sections;

Fig. 82 shows a V-plugged panel that can fit into a square of trusses in any 90° rotated orientation;

Fig. 83 shows how corner plugs of Fig. 79 and either the rhomboidal or V-shaped plugs of Figs. 78 or 81 can occupy the same space of one truss hole;

Fig. 84 shows two storage-"cubbies" comprised of axisymmetric, trussed elements like that of Fig. 74a with various styles of dividers having small corner plugs that locate the dividers at regular intervals along the trussed walls, and in which the dividers can be oriented either horizontally or vertically;

Fig. 85 shows one possible type of a divider with small corner plugs at either end;

Fig. 86 features close-ups of the ends of other possible divider styles all using pairs of small corner plugs;

Fig. 87 shows a side view of the insertion of a divider and how it plugs into a trussed section;

Fig. 88 shows a locating stub element that is used on the opposite end of a divider panel to constrain and fix the divider in a trussed storage-"cubby";

Fig. 89 shows how the locating stub of Fig. 88 engages with the leading end of a divider as it is attached into a trussed wall;

Fig. 90 shows a side and an end view of a plug-in attachment that features an asymmetric joint end orthogonal to the direction of plug insertion;

Fig. 91 shows the insertion of an orthogonal plug-in of Fig. 90 into a trussed wall already having an inserted divider with interfering;

Fig. 92 shows how the axisymmetric joint elements depicted in Figs. 27 and 29 can readily be attached to the orthogonal plug-in of Fig. 90, thus allowing for building structures along orthogonal axes;

Fig. 93 shows plug-ins having different end joint elements: 90° asymmetric (like that of Fig. 27), 45° asymmetric (like that of Fig. 32) and straight barb (like that of Figs. 45 and 46). Plug-ins can also accommodate other joint end geometries;

Fig. 94 shows a door accessory that can slide into orthogonal plug-ins using two elements like that in Fig. 29 but with shafts to accommodate a swinging door;

Fig. 95 shows the front and top views of a door accessory of Fig. 94;

Fig. 96 shows how a door accessory like that in Figs. 94 and 95 and an attached orthogonal plug-in can be inserted into a trussed section over an already-inserted divider attachment without interfering;

Fig. 97 shows a side and two front views of a door accessory that can plug into a trussed wall directly without an attached orthogonal plug-in;

Fig. 98 shows how a divider and a plug-in door accessory like that in Fig. 97 do not interfere and can thus be inserted into or removed from a trussed wall independently of one another;

Fig. 99 shows how a plug-in door like that of Fig. 97 can be inserted over a storage-"cubby" of trussed-walls over an existing divider and next to an adjacent storage-cubby already having a plug-in door and divider in place;

Fig. 100 shows a back plate accessory employing V-shaped plugs like those described with Figs. 81 and 82;

Fig. 101 shows how a back plate like that in Fig. 100 can be inserted over a locating stub of Fig. 88 without interfering;

Fig. 102 shows how a locating stub can be inserted into a truss section after a plug-in back plate has already been attached into the trussed wall structure;

Fig. 103 shows an extender for use on an asymmetric element end to increase the element length;

Fig. 104 shows one possible application of the extender in Fig. 103 in the construction of joined structures;

Fig. 105 shows how the concept of an extender can be applied to other end geometries such as the straight barb geometry;

Fig. 106 shows how the 45° elements of Figs. 32 and 33 can be interlocked without forming a 45° angle;

Fig. 107 shows how the 90° elements like those of Figs. 27 and 54 can be interlocked without forming a 90° angle;

Fig. 108 shows a 90° axisymmetric joint end element with asymmetric barb features;

Fig. 109 shows a close-up of the element in Fig. 108 showing details of the asymmetric barb geometry;

Fig. 110 shows how the configurations of Figs. 106 and 107 are prevented by using asymmetric barb features;

Fig. 111 shows how the axisymmetric elements ends with asymmetric barb features of Figs. 108 and 109 still form the proper interlocking joint like the joints of Figs. 28, 56 and 57;

Fig. 112 shows a truss shaped beam where the cells are triangular and a beam formed not from trusses, but from rectangular (in this case square) cells;

Fig. 113 shows the cross sections of the truss, and a solid section beam with the same amount of material;

Fig. 114 shows how the truss-type extrusion can itself be used to fabricate modular board-like elements which can fit together to form wider plates; and

Fig. 115 shows how the truss-type extrusion can itself be used to fabricate modular board-like elements for uses such as strong lightweight shelving.

THE INVENTION

People's basic needs are food, clothing and shelter. There is also the need for storage, which is directly related to the three most basic needs; food and clothing must be stored, and shelter is the "storage" of people. This set of inventions addresses new solutions to the storage dilemma, as current products and systems leave much to be desired for the home, office and retail space, as previously pointed out. As population grows, the need for storage and the ease of transporting the objects to be stored also increases. This need is evident in both the domestic and business environments, where objects of all sorts must be stored. The storage solutions should be light, modular, versatile, customizable, easy to assemble and disassemble and structurally sound. Material, safety, manufacturing concerns, and the environment must also be considered. Also, the systems should be aesthetically appealing and affordable. In some cases, the systems should be entertaining and fun, and can also be used as teaching aids.

Although, as earlier discussed, some prior designs satisfy the needs of specialized storage solutions, there are few designs that are universal (relating to the larger definition of the storage of person and property); and, as before pointed out, prior designs may not be appropriate to be used in varying storage tasks -- for example, the storage solution of one kind of goods may not at all be appropriate for storage of other objects. Other designs and products in the market, as discussed in the background of the invention, also fail fully to accommodate the wants and needs of users and customers.

The inventions now to be detailed address these concerns and provide designs that also combine form and function into the same product.

The first embodiments describe a modular storage element that also has play-value, provides entertainment and encourages creativity, organization and tidiness in children. Other embodiments are low-cost modular storage solutions the elements of which can be formed by common processes such as extrusions and injection molding, and that require a minimum number of parts. The physical and structural properties and behavior under typical uses and applications are carefully considered and accommodated by the design features, including, but not limited to, barbed interlocking joints, load and moment distribution throughout system members, and element symmetry configurations.

Although well designed for use as modular storage, such as shelving and crate container alternatives, the designs and features of the invention may also be scaled to form larger systems such as shelters, housing construction components and workspace management systems, before discussed, often called office cubicles and integrated furniture systems. The designs may similarly be scaled to form smaller systems such as toy elements and toy sets, accessories to toy systems, and children's entertainment and teaching aids.

A first design relates to modular storage units and plural systems that also have play-value and that also encourage the user to be more creative and neater with their toys. Lego™-type blocks, for example, are universally popular and recognized building toys. If they could be formed also to be able to create storage cubes, the cubes can then become part of an integrated building and play system that would encourage children to have fun while being neat. Drawers and doors may also be added and the cubes used to build usable furniture such as bookcases, desks and a bed platform and the like.

Turning to Fig. 1, a typical large prior Lego™-type plate 1 is shown, formed with large studs 2 and mating socket surface 3, sold under the Duplo™ tradename. Such, however, is not practical to form into a cube from these elements, even if orthogonal surfaces were provided, because, when loaded, the sockets easily pull away from the studs.

The invention remedies this deficiency as illustrated in Fig. 2, through the use of a modified plate 6 with 45 degree angled ends 5 and 8, the 45 degree end surfaces diverging at the ends from the plane of the plate. The inner surface of the plate 6 has studs 7, and the outer surface 9 has mating sockets. Similarly, one 45 degree angled end 8 has sockets on the outside, and the other end 5 has studs 11 on the inside. While the end 5 is bent upwards as shown in Fig. 2 at - 45 degrees from the vertical to the left, the end 8 is similarly bent at + 45 degrees from the vertical divergingly oppositely to the right, and with an externally downwardly inclining crook or step 8, shown making a right angle with the end surface 8, for receiving an end 5 of an adjacent plate 6.

The plate 6 mates with another type of plate 16, shown in Fig. 3, which is in a sense the mirror image of plate 6. Plate 16 also has 45 degree angled ends 15 and 18 corresponding to the ends 5 and 8 of plate type 6, and with the end surface 18 having an inward crook or step 18′ corresponding to the step 8′ of plate type 6. The inner surface of the plate 16 has socketed surface 17, and the outer surface 19 has mating studs 20. Similarly, the 45 degree angled end 18 has sockets 19 on the outside, and the other end 15 has studs 21 on the inside.

Fig. 4 shows how plates of the type shown in Figs. 2 and 3 may be combined to form a cube 100. Two plates 6e and 6d are of the type of plate 6 shown in Fig. 2. They have studded surfaces 7e and 7d on their inner surfaces and socketed surfaces 9e and 9d on their outer surfaces, respectively. It should be noted how their opposite ends of the type 5 and 10 shown in Fig. 2, mate together with studs and sockets. Because the joint is made at a 45 degree angle, it prevents the bottom of the cube from dropping out when the cube is loaded and supported from the sides, such as when an array of cubes is to be formed into a bridge structure, say, for example, spanning the workspace of a desk. The corners nest tightly to create a strong joint. For example, end 5d of plate 6d nests tightly in the step or crook 8e′ of end 8e of plate 6e.

The other two sides of the cube 100 are formed from plate type elements 16e and 16d that are of the form 16 shown in Fig. 3. Here, the inner surfaces 17e and 17d are socketed and the outer surfaces 20e and 20d are studded. Once again, the sockets and studs of the 45 degree ends allow the plates 17e and 17d to join with the other plates 16e and 16d to complete the cube 100. The result is a cube 100 with beveled corners and studs on two exterior adjoining sides, and mating sockets on the other two adjoining sides.

An impediment to the sale of many prior modular storage devices is the fact that the producer is shipping a lot of air, and the retailer has to use a lot of shelf and storage space, which is costly. Shipping the cubes as plates which are then assembled, on the other hand, creates a huge cost saving. In the case of the cube, for example, shown in Fig. 4, the sides can be glued together after assembly. A high quality PVC type of plastic, such as used by Lego™, can easily be glued together using PVC pipe cement. This melts the plastic together, and the resulting fused joints create a cube as strong as if the entire cube had been molded at once. Of course it is also considered in the spirit of this invention to mold a cube all at once, if desired, with studs (bumps) on two of the sides, and sockets on two of the other sides, such that the cubes can be stuck together and the joints bridged with cap plates, as shown in Figs. 5 and 6.

While this cube by itself will not be able to resist large shear loads which could cause it to fold up into a rhombus shape, when several such cubes are joined together, with exterior studded surfaces mating with exterior socketed surfaces, however, a very sturdy array is formed, as shown in Fig. 6. Here, the four cubes 100a, 100b, 100c, and 100d are stuck together. Exterior joints are strengthened, shown only on the bottom joint in the drawing, with standard plates of the type shown in Fig. 1. Plates 1c, 1d, and 1e bridge the bottom joint greatly to rigidify it and prevent the system from collapsing into a rhombus. A back plate, with studs pressed into sockets on the ends of the plates, may also be used to give shear strength.

The detail that enables this rigidifying effect to occur is more clearly shown in Fig. 5. Elements 16a and 6a of the cube 100c form a joint with elements 6b and 6c of another cube 100d. Element 16a has an angled end 15a with studs 21a that mate with the socketed exterior surface of angled end 8a of plate 6a, which, in this example, happens to have studs 7a on its inside surface. Similarly, element 6b has an angled end 8b, the socketed outside surface of which mates with sockets 11c on the angled end 5c of element 6c. Element 16a has studs 20a on its outside surface, and these will mate when pressed together with sockets on the outside surface of element 6b. This provides a very effective joint to transmit shear loads. It can, however, be pried apart by tensile loads. To prevent this from happening, the bottom plate 1b is employed. The bottom surfaces of both adjoining cubes plates 6a and 6c have socketed exterior surfaces, so the studs 2a of plate 1a can be pressed into them to form a bridge that is effective at transmitting tensile forces across the bottom surface of the joint, thereby preventing the plate elements 16a and 6b from being pulled apart.

This type of joint that mixes strength directions of studs and sockets so that shear capability in one direction prevents a neighboring differently oriented set from being pulled apart and vice versa is the essence of this embodiment of the invention. The 45 degree element based joints are one embodiment that through the principle of a triangle as a brace, creates a very rigid joint when cubes are pressed together and a flat plate is pressed to the joint to form the chord of a triangle with the 45 degree elements. Different types of angles may also be used and will occur to those skilled in the art of joint design.

To illustrate the different types of joints that can be used in accordance with the invention, consider the plate elements in Figs. 7 and 8 which have simpler designs than the plate elements of Figs. 2 and 3 and hence will be less costly to mold. In Fig. 7, plate element 76 has angled ends 75 and 78, but they are not cantilevered from the main surface of the plate and therefore allow for easier mold design. The end 75 has socketed surface 81, and the other end 78 has studded surface 80. The inside of the plate has studs 77 and the outside surface 79 has sockets. In a mirror image fashion, Fig. 8 shows a plate 86 where the inside surface 87 is socketed and the outside surface has studs 90. One end 88 is angled inward and has studs 89, and the other end 85 is also angled inward and has a socketed surface 91.

Fig. 9 shows how two elements 76d and 76e with studded surfaces 77d and 77e and exterior socketed surfaces 79d and 79e are joined together, studded end 78e to socketed end 75d. Similarly, elements 86e and 86d with interior socketed surfaces 87e and 87d and studded exterior surfaces 90e and 90d are joined together and then with elements 76e and 76d to form a cube 100g. Cube 100g is somewhat more prone to racking (collapse under shear loads), so it should be joined to other cubes, where the same principles of the joint shown in Fig. 5 may be used greatly to rigidify the elements.

Variations of the elements 76 and 86 of Figs. 7 and 8 are shown in Figs. 10 and 11. Element 150 in Fig. 10 is similar to element 76 of Fig. 7 except that element 150 has an extra stud 156 and socket 155 on end 152 and also an extra stud 154 and socket 153 on end 151. Element 160 is also like element 86 but has extra stud 164 and socket 163 on end 161 and extra stud 166 and socket 165 on end 162. Elements 150 and 160 form storage-"cubbies" as shown in Fig. 12. Elements 150a, 150b, 160a and 160b form cube 120 in the same fashion as described in connection with the embodiment of Fig. 9. The addition of two-stud-two-socket plates 170a-h, which are currently available as the before-described Duplo™ blocks, increases the cube strength as the flat plates 170a-h mate with the added studs and sockets of the wall elements. For example, plate 170a mates with extra stud 156a on wall element 150a and stud 166b on element 160b in the interior of cube 120. Plate 170g also mates with stud 164b on element 160b and stud 166a on element 160a in the interior of cube 120. Plates 170c and 170e also mate on extra studs in the interior of cube 120. Studs on plates 170b, 170 d, 170f and 170h mate with the sockets on wall elements 150a, 150b, 160a and 160b on the exterior of cube 120. The added plates 170a-h do not extend beyond the square frame boundaries of cube 120 so that arrays of cubes can be formed. As an example, Fig. 13 shows two cubes 120a and 120b mated along one side using the elements of Figs. 10 and 11 and the basic two-stud- and two-socket-plate elements of Fig. 12. The addition of the mating plate elements greatly increases the racking resistance of a single cube as there now exists mating in two directions at each corner of a cube, one from the mating ends of wall elements and one from the orthogonally-mating plate attachment.

In the formation of the cubes as shown in Figs. 9 and 4, when the cubes are put into an array as shown in Fig. 6, the interfaces between the cubes create double walls. To eliminate the cost of such, where desired, a double pronged end element may be used as shown in Fig. 14, the element 406 has a studded surface 407 and a socketed surface 409 on the other side, with the prongs diverging at + and - 45 degrees to the plane of the plate above and below the plane as shown. One end has a 45 degree prong 405 extending above the plate with bumps 411 on one side. On the same end of element 409, there is now provided a second opposite 45 degree prong 413 below the plate with a socketed surface 412. The other end is like a mirror image, with the upper 45 degree prong 408 this time having socketed surface 410 and its lower 45 degree prong 415 having a studded surface 414. Similarly, in Fig. 15, element 516 is like a mirror image of the element 406 in Fig. 14. One surface 517 is socketed and the other surface 520 is studded. One end has a 45 degree prong 515 with studs 521, and the neighboring 45 degree angled surface 524 has socketed surface 525. At the other end of the element 516, there is a 45 degree angled prong 518 with socketed surface 519 and a neighboring 45 degree angled surface 522 with studded surface 523.

Fig. 16 shows how these elements can be used to form cubes, in which, now, the adjacent walls of cubes are shared. The exterior walls of the cubes may be made from elements of the type 6 and 16 in Figs. 2 and 3 respectively. Cube 400a is made from elements 6h, 516a, 406a, and 6i. Cube 400b shares element 516a with cube 400a and has its other sides made from elements 6g, 516c, and 406b. Cube 400d shares element 406b with cube 400b, and has its other sides made from elements 516d, 405d, and 516b. Note, for example, that element 516d can be used to continue the sequence of cubes; but element 406d terminates the upward growth of cubes. Cube 400c shares sides 516b and 406a with cubes 400d and 400a, respectively. Joining plates 1h, 1k, and 1n are used to tie together and rigidify the joints between cubes 400a and 400b, 400a and 400c, and cubes 400c and 400d, respectively. Thus rigid joints are formed as shown in detail in Fig 5. Plate elements 1i, 1g, 1j, 1l, 1m, and 1o merely make the remaining surfaces flat and even with the joining plates.

All of the Lego™-type cubes, furthermore, can also have studs molded into the edges, so that large plates can be pressed onto the backs of the cubes to give them greatly increased shear strength. This will help hold them together and help prevent them from folding up into rhombi when side loads are applied.

The fundamental use of interlocking elements with mirror image ends to form joints resistant to loads that would otherwise pull the joints apart or shear them into rhombuses can be evolved to include a class of extruded shapes that are slid together along an axis parallel to the joint instead of being pressed together in a direction normal to the joints, which, indeed, makes the joints susceptible to being pried apart and hence may require bracing. Embodiments of this concept are shown in Figs. 17 through 68. The uniqueness of this idea is that one basic type of extruded element forms the walls and the joints of the cubes, so a minimum number of pieces is required, as opposed to previous attempts in the prior art to form series of dovetails that are then locked together with separate mating keys, as before described.

The first and simplest of this type of embodiment is shown in Fig. 17, where a plate element 200 is formed with two rounded dumbbell-like protuberances 201 and 202, extending transversely at right angles to and above and below the plate on one end and which are below the plate on one end and which act as keys in a joint, and a block 203 with rounded hollows receptacles 204 and 205 on the other end which act as key ways in a joint. Fig. 18 shows just a block element 303 with hollow cavities 305 and 304 that would be used as a terminator element. Similarly, Fig. 19 shows a terminator element 306 with rounded protuberances 301 and 302.

These simple elements 200, 303, and 306 are combined to form a series of cubes as shown in Fig. 20. Cube 250 is formed by elements 200b, 200c, 200d, and 200j. The joint between 200b and 200c is completed with the use of terminator 306a and the element 200a which also is used to form another cube in the series. Similarly, the joint between elements 200b and 200j is completed with elements 200l and 200k that are usable to form other cubes. The joint between sides 200j and 200d is completed by elements 200i and 200h that also are used to form other cubes. Finally, the joint between element 200d and 200c is completed with terminator 303a and element 200e that is used to form neighboring cube 251. Cube 251 is thus formed from elements 200d (which it shares with cube 250), 200e, 200f, and 200h. The joint between sides 200e and 200f is completed with terminators 303b and 306b, and the joint between elements 200f and 200h is completed with element 200g and terminator 306c.

It can be seen from the geometry of the key and key-way forms of the ends of the elements, that the joints themselves resist all forms of loads that would be applied to and otherwise act to deform the cubes. As moments and loads are applied, however, the rounded keys tend to spread apart the rounded key-ways by a wedging action. This requires substantial strength to be built into the key-way elements to prevent this spreading action. Similar spreading may also occur when a dovetail shape is used.

Where this is of concern, a generation of a more complex joint is desirable, but one that is self-locking, so the pry-apart forces that cause the round key ways to spread, actually cause the keys to become more tightly locked and integrally to hold the key ways together to prevent spreading. A natural shape with which to accomplish this goal, in accordance with the invention, is that of a barb. In a manner similar to that of a fish hook, the more load that is applied, by either a swimming fish or a heavy load of books, the barb grabs harder and resists being pulled out.

Once again, the goal is to create a single extruded element, that, for example, can be made from thick sections of inexpensive materials, such as regrind plastic (e.g., from recycled milk bottles or reclaimed polyvinyl chloride) that can be interlocked to form as large an array of interlocking storage cubes as may be desired. In schools, for example, such an array of "cubbies" provides a place for each child to place work, lunch boxes, outdoor clothes, etc.

Fig. 21 shows the fundamental element of this modified system. Here a single piece extrusion 500 has a double arrow-like barb on one end with elements 502 and 503. These barbs are shown in greater detail in Fig. 23 which shows them as part of a terminator element 524 similar to that of 306 in Fig. 19. The barb 520a, and similarly its symmetric partner 520b, has a shank 521 and a head 523. The barb points 522a and 522b grab in corresponding female barb arrow-shaped opening cavities or receptacles in the mating end, such as shown in Fig. 22. The other end of the element 500 in Fig. 21 has the female mate 504 to the male barb 501. The female receptor 504 has a barbed internal cavity 506, bounded by barbed arms 505 and 507, and cavity 509 is bounded by arms 510 and 508. Fig. 22 shows an end terminator similar to terminator 303 in Fig. 18, with the cavities 543a and 543b bounded by barbed arms 541a and 541b, and barbed arms 542a and 542b, respectively.

In an assembly, an element similar to 500 has its male barbs slide into the cavities and snugly fit. When loads are applied to the joint, the tendency would be for the joint to try and pry itself apart; but the barbs catch on the internal barbed features and they will lock up. Fig. 24 shows a cube 600 made from these types of elements. Identical elements 500a, 500b, 500c, and 500d make up the walls of the cube. Additional similar elements can be added by sliding the male barbed ends into female barbed receptors to create a matrix of cubes that grows in any desired direction. Just a single cube is shown, where the corners are completed and given structural rigidity using the terminator elements shown in Figs. 22 and 23.

Fig. 25 shows the detail of a joint between elements such as 500 in greater detail. Plate elements 550, 551, 552, and 553 all come together at the intersection of 4 cubes. Element 551 has male barbed ends 551a and 551b that mate in receptor 550a on the end of element 550 and in receptor 552a on the end of element 552. Element 553 has a male barbed end 553b that mates with receptor 550b on the end of element 550. Element 553 also has a male barbed end 553a that mates with receptor 552b on the end of element 552. The result is a very rigid self-locking joint that approaches the strength of a solid molded joint. Indeed, to lock it into place, a self threading screw can be threaded into the cavity 556 at the center of the joint, if desired. A long bolt or screw may also extend through the hole 556 to anchor the unit to a wall.

This novel self-locking barb joint can be made, for example, from extruded aluminum, or even from extruded plastic. Where heavy loads are to be supported, a more complex extrusion can be made that essentially forms a truss element, instead of a simple plate as shown in Fig. 21, to join the male barbed end to the female receptor end. If an aluminum extrusion is used, this truss with closed cells may be directly extruded. A plastic extrusion can be made also; for example, a two-piece plastic extrusion where the top chord of the truss is attached to the barbed male and female ends. The lower chord of the truss and the diagonal braces may be a second extrusion and they would slide into the first. The joints may, for example, be of the circle and socket type shown in Fig. 20. Fig. 26, shows the extruded truss design 560, where top chord 561 and bottom chord 562 are connected by diagonal elements such as 563. One end of the extrusion has a male barbed element 564 and the other end has a female barbed element 565.

As a further modification, in Fig. 27, another barbed element like that of Fig. 21 is shown, but now with axisymmetric end features. Element 600 has a plate component 615 connecting two ends 610a and 610b. These ends 610a and 610b are exactly the same when given a 180° rotation about the center of the plate center. Each end has one male barb 614 (shown on end 610a) and one female barb mate 612 formed by barb arms 611 and 613. Fig. 29 shows a terminator element 620 having the same features as each end of element 600 to serve in the same joint completion role as terminator elements in Fig. 22 and 23. Since the end features are axisymmetric, however, the joint requires only one geometry of termination, also axisymmetric, as opposed to the two symmetric geometries of Figs. 22 and 23. This results in less expensive manufacturing and inventory costs since only one design of the barb-and-mate features is required, and only two basic elements (one wall and one terminator) must be produced, distributed and stored. Such simplicity reduces storage-"cubby" construction and the number of unused parts since it is less confusing in determining how many pieces of which terminator type are required to complete an array of cubes.

Simplicity in piece-part count is further shown in Fig. 28 -- a detail of a joint comprising four elements 600a, 600b, 600c and 600d. The barbs interlock with the neighboring element female barb mate. For example, barb 614d on element 600d interlocks with barb mate 612a on element 600a. Similarly, barb 614a engages with barb mate 612b of element 600b. This joint is structurally equivalent to the joint shown in Fig. 25, using the mechanical properties of barbs and the compression and tension effects of a mostly filled joint cross-section. Fig. 30 shows a storage-"cubby" structure made up of elements shown in Fig. 27 and 29, along with a diagonal element 630 having ends of the same one-barb-one-mate geometry. Again, the completed four-element joint at each corner of the cube is strong against diagonal loads that cause other non-barbed joint designs to collapse or come apart.

Fig. 31 shows a storage-"cubby" formed with axisymmetric elements 640a, 640b, 640c and 640d using trussed designs of the basic element 600. Element 640a, for example, has the same one-barb-one-mate ends 642a and 642b, while the wall component is formed with truss members 641a. Again, the truss design provides greater strength-to-weight ratios and can be extruded in plastics and aluminum, for example.

In Figs. 27-31, the angle between joined members is 90°. By defining N as the number of members completing a joint, in this case N=4, then it is clear that the product of N and the angle between mated members is 4 x 90° = 360°, or a complete circle or "circuit."

Since the axisymmetric geometry of element 600 in Fig. 27 forms a "closed circuit" of connection as shown in Fig. 28, axisymmetric design can be used to form joints with different mating angles between wall elements. Or, the number of elements can theoretically be any integral number, and the joining angle between mated elements is thus 360°/N. Fig. 32 shows another axisymmetric structural member 800 similar to that in Fig. 27 but designed for N=8. This end design allows eight elements to form a strong, complete joint in which the mating angle is 360°/8 =45°.

This element 800 has a wall or plate component 815 and ends 810a and 810b. Each end has a male barb 814 and a female barb mate 812. In this particular end design, a faceted end surface 816 is provided. Fig. 33 shows a close-up of the end of this element. Barb mate 812 is formed by barbed arms 811 and 813. Fig. 34 shows the same end features on a terminator element 820: a mate barb 824 and a female mate 822 formed by barbed arms 821 and 823. The difference in this design is that the angle between the male barb centerline and the female mate centerline is more obtuse that the particular designs shown in Figs. 27-31. This, in some instances, is more desirable in a joint because the direction of force resulting from the barb engagement approximates a circular circuit of force distribution throughout a completed joint, and is also defined by the axisymmetric condition that all end members have the same geometries if only one barb and one mate per end are used.

Fig. 35 shows a longer element 830 like element 800 also having the same ends with a barb 834 and a mate 832 formed by barbed arms 831 and 833, but a longer plate segment 835. Fig. 36 shows a central core element 840 having a center through hole 841 and a faceted outer surface 842. Fig. 37 shows a completed joint using elements of Figs. 32 and 35 and a core element. Short elements 800a, 800b, 800c and 800d and long elements 830a, 830b, 830c and 830d complete a barbed closed circuit joint. For example, barb 814a on element 800a engages with female mate 832a on long element 830a, while barb 834a on long element 830a engages with female mate 812b of short element 800b. Center core 840 engages with faceted surfaces of the element ends, making the joint even more rigid. The faceted surface not only compresses the joint material essentially to pre-load the joint, but also opposes any twisting of an element from the immobility of the core element. For example, faceted surface 816a on element 800a meets with faceted surface 842a of the core piece. When element 800a undergoes a twisting force with an axis parallel to the joint axis, the faceted surface interaction opposes such an action as the center core 840a is considered rigid, and the faceted surfaces engaged with the faceted end surfaces of the other element also prevents the center core from rotating in reaction to the twist force on element 800a. The core element also has through hole 841a which allows for a bolt to run the length of the joint to lock the joint together and prevent the de-sliding detachment of elements or to anchor the structure to a wall. The compression of the center core, by a tightened nut and bolt through the hole 841a, for example, may be used to cause an expansion in the radial direction of the core to further pre-load the joint, particularly if the center core is made of a material with an appropriate Poisson's ratio.

Fig. 38 shows a side piece 850 that has a male barb 852 and a female barb mate 851 having the same shape as the element barbs and mates of Figs. 32-35. It also has a faceted inner surface 853. This side piece is equivalent in features to three joined terminator elements 820. Fig. 39 shows one use of such a side element in a joint. Two elements 800e and 800f are oriented 180° from one another. Two side elements 850a and 850b mate with the wall element barbs and mates. Core piece 840b completes the joint. The joint in Fig. 39 shows that two shorter elements can be joined to form a longer element, in case a user wants a longer wall. Obviously, one side piece 850 can be used on an edge joint location in an array structure to minimize the number of individual terminator elements 820 required to complete the joint; that is, one side piece would replace three mated terminator elements.

This principle is applied to the corner element 860 in Fig. 40. This corner piece is equivalent to five mated terminator elements, as it has a barb 862 and barb mate 861 and an inner faceted surface 863. Fig. 41 shows one application of such a corner element. Wall elements 800g and 800h join with terminator element 820a and corner element 860a, with center core 840c. The barb 814g on element 800g engages with mate 861a on corner element 860, and barb 862a on the corner piece engages with mate 812h on element 800h.

Fig. 42 shows a possible structure using the 45° joining elements of Figs. 32, 34, 35, 36, 38 and 40. The side and corner elements simplify the edge joints of the structure, thereby reducing joint size and thus weight, providing a single, smooth, flat surface along the joint length. By using side and corner elements, moreover, any fit mismatches resulting from using multiple terminator elements are eliminated, thus making the joint stronger.

The barb and compressing element end surfaces are also used in another modified joint design. In Fig. 43, four wall elements 705a, 705b, 705c and 705d have single, symmetric female barb mates, mating with a center piece 700 which has four single male barbs in the shape of a cross. For example, barb 701a on the center element 700 mates with barb mate 706a on element 705a, and barb 701b on center element 700 mates with mate 706b on element 705b. The surfaces of the elements also meet with the center piece surface, strengthening the joint. The faceted end of element 705a, for example, meets with the surface of center element 700 at location 703a. At locations 704a and 704b the faceted end surface of element 705b meets with that of element 705a and 705c, respectively.

Fig. 44 shows the single symmetric barb design in reverse. The center piece 710 has female barb mate features 711a, 711b, 711c and 711d. Also designed into the element are diagonal female mates 712a-d. As in Fig. 43, wall elements join with the center piece using the single barb and single mate engagement. The diagonal features now, however, allow wall elements having male barbs to join with the center piece at 45° angles to the basic joined elements. Fig. 45 shows the end of such a wall element 720 having a single male barb 721 on each end. For simple tooling in manufacturing, element 720 has a solid cross-sectional wall component 722. For greater strength-to-weight properties, a trussed element 730 can also be used, having the single male barb 731 and truss geometry 732.

Fig. 47 shows a connector element 735 which can be used to couple two elements of type 720 or 730 for lengthening, or when the full multi-directional cross-piece of Fig. 44 is not needed. Fig. 48 shows the joining of wall elements 720a and 720b with the connector piece 735a, which provides the same end-to-end distance between elements as would the center piece 710 in Fig. 44.

Fig. 49 shows an array of storage-cubbies made of shorter horizontal and vertical wall elements and longer diagonal elements joining with the multi-mate-featured cross-piece of Fig. 44. The joint is considered complete with only the horizontal and vertical wall elements since the full compression and tension condition still applies without diagonal members. Adding diagonal members or terminator elements in the 45° mate locations in the joint center piece would, however, further strengthen the joint.

The same structures of the above-mentioned embodiments can also be applied to more user-customized designs. For example, the wall elements in Figs. 17, 21, 26, 27, 32, 35 and 45 all include the wall component integral to the whole element. The elements in Figs. 50 through 68 decouple the end component from the wall component while maintaining the same structural system capabilities.

Fig. 50 shows the single male barb end clip 750. The male barb 751 is the same as elements 720 and 730 in Figs. 45 and 46 respectively, and will thus mate with female mate elements such as that of Fig. 44 and the connector element of Fig. 47. This end clip, in addition, has an open jaw and gap in which a separate wall component element can be attached. The jaw is comprised of jaw walls 752a and 752b which have jaw teeth 753 on the interiors. These teeth are used to grip and engage a wall element. Stop limit tabs 754a and 755b provide an end limit for inserted wall components, while open arch 756 not only reduces cross-sectional area (important for extrusion simplicity and cost) but provides a convenient through-way for a long bolt to anchor the element to a wall or other structure. Shoulders 755a and 755b add strength to the clip structure and also increase joint rigidity by engaging more surfaces with a joint center cross-piece, simultaneously bracing diagonal clip elements shown in Fig. 52.

Fig. 51 shows the end clip 750a mated with a wall component element 760, which can be any common shelving material, such as wood, plastic, or composite or the like. The end surface 761 of wall element 760 is stopped at limit tab 754c while the jaw teeth are embedded into the wall material. For example, teeth 753a on jaw wall 752c engage with the wall surface 762a, while teeth 753b of jaw wall 752d engage with wall surface 762b. The remaining voids between the jaw wall and the wall component 760 can also be filled with glue or epoxy, if desired, to provide more gripping structure. The wall element 760 can be pressed into the clip either in the direction of the clip centerline (horizontally in Fig. 51), which will tend to spread the jaw walls, or in the direction of the clip joining axis ("into the page" in Fig. 51).

Fig. 52 shows a joint of end clips 750b-e with wall elements 760b-e attached, all mating with center joint piece 710a. An end clip 750f with wall element 765a engages with the center piece 710a. It can be seen that clip shoulders 755e and 755f on clip 750e abut center piece shoulders 713a and 713b, strengthening the attachment of clip 750e into the center element 710a. Also, on diagonally-attached clip 750f, having no center piece shoulders available to abut, clip shoulder 755c rests on clip wall 752c of clip 750c, and clip shoulder 755d rests on clip wall 752d of clip 750d. This adds strength to clip 750f in wall element 765a. A portion of a structure made of elements detailed in Figs. 50-52 is shown in Fig. 53. So long as the diagonal wall member has proportionate length to the cube sides, the storage-"cubby" opening can be scaled to practically any size.

Fig. 54 shows an end clip similar to element 750 but with a different joint end geometry. End clip 770 has joint end 771 of the axisymmetric one-barb-one-mate geometry for 90° inter-element angle connection. The jaw has jaw walls 772a and 772b with jaw teeth 773. Inside the jaw are limit tabs 774a and 774b and open arch 775. This end clip functions in the same way as the clip in Fig. 50. Fig. 55 shows this 90° axisymmetric clip 770a with wall component element 776. Fig. 56 shows a close-up of a joint. End clips 770b-e with wall components 776b-e attached interlock and complete a joint. Since all wall members are at 90° to one another, the structures that can be made with the axisymmetric end clips, and custom-length walls are more variable than fixed wall-length structures. For example, Fig. 57 shows a portion of a structure formed by end clips and wall elements. Wall elements 777a, 777b and 777c are horizontal cross members of equal length, while wall elements 778a, 778b, 779a and 779b are vertical members. However, members 778a and 778b are equal in length but are shorter than members 779a and 779b. Thus, by using wall members of different lengths, variable opening storage-"cubbies" and shelves can be constructed easily.

Fig. 58s illustrates a bridge-type structure that can be assembled using 20 terminator elements, 44 end clips, 8 short wall elements, 12 medium-length wall elements, and 2 long wall elements. Fig. 58b shows a structure with variable-size storage openings that is made with the exact same number of terminators, end clips, and wall elements as in Fig. 8a. While the number of T-joints, cross-joints, corners joints, and extension joints differ between the structures in Fig. 58a and Fig. 58b, however no additional joining elements are required, nor are there any leftover elements not used when changing structures, despite the differences in joint configuration. For other structure configurations, a minimal number of extra elements (either terminators or end elements) may be required, as opposed to obtaining addition T-brackets, elbow-brackets and cross-brackets. The end elements and terminator elements can be interchanged to form T-, cross- and elbow-joints. Also, one would only need to acquire additional end elements and terminators, as opposed to obtaining, for example, a cross-bracket to replace a T-bracket that would then go unused and wasted.

The use of end clips with separate wall elements also allows the user to select wall component size and material according to specific needs. One of the major deficiencies of commonly-sold plastic crates is that the crate sides tend to buckle when the crate opening faces the side. The walls are often not sufficiently stiff to prevent this mode of deformation, not evident when stacked with openings upwards. The use of separate wall components allows a user to select a more appropriate material to prevent this buckling. For example, standard thickness pine wood boards can be used, which has greater stiffness than the relatively flexible plastic used in retail crates, and is cost-competitive as well. For lighter or heavier storage loads, boards of other thicknesses and stiffnesses can also be used instead. In stores, pre-attached board-and-clip products can be sold alongside separate boards of varying length and separate end clips. Thus, the customer wanting ready-made, minimal-assembly shelving solutions can purchase the pre-attached products, while customers with other structure requirements can buy separate pieces and boards, and also have the boards cut to specific dimensions on-site or elsewhere.

The boards, furthermore, need no special finishing or preparation; and whereas other shelving methods require dovetail grooves or other end features to be made, the boards of the invention need only be cut to length with no special features to fit with the end clips.

For added gripping strength between end clips and wall components, screws can be used. Fig. 59a shows a single barb end clip 750g mated with a wall element 780a. Flat-end screws 781a and 781b can then be driven into the assembly further to prevent detachment of the wall from the clip. The flat-head screws provide this engagement while not rising above the clip jaw wall surface. However, if the clip is made of a relatively brittle material, flat-head screws can cause unwanted fracture at the screw hole. In this case, flat-underside screws such as panhead or roundhead screws can be used. Fig. 59b shows such usage. 90° axisymmetric barb end clip 770f is engaged with wall component 780b, while screws 781c and 781d thread into the two sides of the wall piece.

Fig. 60 shows another variation of the end clip. 90° axisymmetric end clip 792 has less-protrusive teeth 793 that provide a constant open gap width. These flat features also provide more surface area on which adhesives can join to a wall element without marring or penetrating the wall surface.

For applications and structures in which wall components are to be of different wall thicknesses, the end clips can be made with different jaw gaps without affecting joint assembly. For example, Figs 61a-c show the 90° axisymmetric end clip with different gap widths. Clip 792a is mated with wall element 780c, while clip 792b and clip 792c are mated with wall elements 780d and 780e of decreasing widths, respectively. Despite the different wall thicknesses, these clip-and-wall assemblies can all join together because the joint ends remain the same.

Fig. 62 shows that the end clips can be attached to different edges of a wall element. Clip 790a mates with wall edge 786 at interface 791a while clip 790b mates with wall edge 787 at interface 791b. Note that, if desired, the angle ß at corner 788 between edges 786 and 787 need not be 90°, and thus structures need not be built in equiangular configuration. Wall element 785, for example, could be any polygon shape and have attached end clips and wall components on any and all of the polygon edges.

Fig. 63 shows another end clip 870. This end clip has non-protruding back-angled jaw teeth 871 and a limit tab 872. Fig. 64 shows a trussed wall element 875 with mating teeth 876a-d. These elements can be used to form a clip-and-wall assembly as shown in Fig. 65. End clips 870a and 870b attach to the trussed, toothed wall element 875a. The teeth 871a on clip 870a mate with the teeth 876e on the trussed wall as the end of the wall element abuts limit tab 872a. This assembly may be used without added screws or assemblies as the back-angled teeth function similarly to the barbs ends; up to a strength limit, the harder the wall element is pulled, the stronger the resistance.

Obviously, other joint end geometries may be employed with the non-protruding constant gap width teeth. Fig. 66, as an example, shows the symmetric single male barb with back-angled teeth.

Fig. 67 shows a completed axisymmetric joint using two end clips 870c and 870d and two terminator elements 874a and 874b. An equivalent connection element 880 is shown in Fig. 68. This connection element has the same back-angled teeth 882a and 882b and a trussed midsection, which reduces component cross-sectional area, thus lowering manufacturing cost and decreasing component weight while providing equivalent structural properties.

These constant-gap clip elements of Figs. 63, 66, 67 and 68 can be used with common wall elements, as shown in Fig. 69a. End clips 870e and 870f engage with wall elements 885a and 885b respectively, while a connector element 880a mates the wall elements. The gaps 883a-d provided by unfilled teeth voids can be partially filled with a glue, adhesive or epoxy, again adding more strength to the interface. These same end clips and connectors can also be used with appropriately-toothed wall elements as shown in Fig. 69b. End clips 870g and 870h mate with trussed wall elements 875b and 875c respectively, while connector 880b mates the two wall elements.

The embodiments described above mainly involve the design of the joint ends. However, the structural systems can be further described and developed by novel design of the wall members; specifically by a truss design that provides both structure and features with the same physical members. A truss maximizes the strength-to-weight ratio, and thus minimizes cost. These design considerations and the related attachments also involve the joint embodiments described above.

Fig. 70 shows a corner joint element 887 equivalent to two interlocked end clips. Fig. 71a shows that corner element 887a can interlock with terminator 874c and end clip 870i to form a T-joint. It is evident that a single piece T-element can similarly be made, with or without barb features to accommodate an interlocking element or terminator. Fig. 71b shows a cross-joint comprising of two corner elements 887b and 887c. Again, a single cross-piece element may be made.

Fig. 72 shows a wider-jaw end clip 890 like that in Fig. 63 next to two thickness adapter elements 892a and 892b. The end clip 890 has jaw teeth features 891, and the thickness adapters have outer teeth features 893a and 893b, and inner teeth features 894a and 894b. Fig. 73a shows how one set of two thickness adapters 892c and 892d mate with the end clip 890a. For example, top thickness adapter 892c has outer teeth

893c mating with end clip jaw teeth 891a. Separate wall element 895a fits inside end clip 890a between the thickness adapters. The top surface of wall 895a interfaces with inner features 894c on thickness adapter 892c. Fig. 73b shows that a second set of thickness adapters 892f and 892g can interface with the outermost set of thickness adapters 892e and 892h which are interlocks with end clip 890b. The wall element 895b, thinner than wall element 895a in Fig. 73a, can then reside between both sets of thickness adapters in the end clip. These thickness adapters allow a single design of an end clip to accommodate different thicknesses of wall elements. Also, as with the elements in Figs. 60-61, the end clips will still interlock with one another as long as the end features are the same, regardless of wall thickness.

Fig. 74 shows two trussed wall elements. Fig. 74a shows an 90° axisymmetric-joint element 900 with axisymmetric truss design. A rotation of 180° results in the identical element. The wall component is composed of outer walls 901 and 902, with truss members 903. Each truss hole 904 is formed having a major vertex 905 and two minor vertices or corners 906.

Fig. 74b shows a 90° axisymmetric-joint element 910 with single-axis truss symmetry. A mirroring of the element along the centerline shown results in an identical truss (although the joint ends are not identical as they are axisymmetric). The wall element has two outer walls 911 and 912 separated by trusses 913. Each truss hole 914 has a major vertex 915 and minor vertices 916. The following derivations and development will be carried out with respect to the axisymmetric truss of Fig. 74a, but can be similarly done for the symmetric truss of Fig. 74b.

Fig. 75 shows one half of an axisymmetric truss wall with structural element variables: overall element thickness T; element length L; wall thickness t_{wall}; truss wall thickness t_{truss}; truss angle ß; minor vertex radius $r(ß)$; major vertex radius r^*; center-to-center spacing l.

Some of these variables are dependent upon manufacturing constraints and best-practices. However, these constraints can be met while other non-critical dimensions can be optimized for functional reasons. For example, truss thickness t_{truss} is often thinner than outer wall thickness t_{wall} due to cooling rates in extrusion processes.

Functionally, if these trusses can be made geometrically symmetric, then accessories can be attached with proper fit and guaranteed alignment, while still allowing for user changes and variation. A critical feature in the truss is that at 901b the wall thickness t_{wall} must be equal to the wall thickness at the major vertex of the truss hole 904b at 902b, as shown in Fig. 76.

As depicted in Fig. 77, rounded square center plugs 920a and 920b can be inserted truss holes 904c and 904d. These plug corners each have a radius r^*(plug) equal to r^*(hole), the radius of the truss hole. If these radii are designed properly, the centers of plugs 920a and 920b will be along the centerline of the trussed wall. This condition ensures that plug 920a has a vertex 921a fitting into the major vertex 905c of truss hole 904c while the opposite plug vertex 922a is tangent to the truss hole edge. Similarly, on plug 920b, top vertex 921b is tangent to the edge of truss hole 904d while opposite plug corner 922b fits in the major vertex 905d. Fig. 77 thus also shows that a rotation of a rounded square plug by any multiple of 90° or the placement of a plug into any truss hole does not change the center of the plug with respect to the wall centerline.

This special situation can be calculated from geometric analysis. The major vertex radius r^* (in Fig. 75) of a truss hole is given by Equation (1):

$$r^* = t_{wall}\left(\frac{\cos\beta - \frac{t_{truss}}{2t_{wall}}}{1-\cos\beta}\right) = \frac{t_{wall}\cos\beta - \frac{t_{truss}}{2}}{1-\cos\beta} \qquad (1)$$

Referring to Fig. 78, consider a trussed structural element 900b and an accessory 930 with center plugs 920c-f. The accessory can plug into the structural cross-section regardless of the accessory being "up" (Fig. 78a) or "down" (Fig. 78b) if the plugs and major vertices of the truss holes have radii r^* determined by Equation (1).

Fig. 79a returns to a similar truss section 900c of Fig. 78 but now with an overlaid accessory 940 with small corner plugs 941a and 941b in truss hole 904d at its minor vertices. Fig. 79b shows the same accessory 940 rotated 180° fitting into the trussed element 900c. However, corner plug 941b now engages with a minor vertex of truss hole 904c while corner plug 941a fits into a minor vertex of 904e.

A close up of either plug is shown in Fig. 80. The plug 941 has acute angles of corners 942 and 943 of ß°, the same as the angle of the minor vertices of the truss holes 904 in Figs. 75-79. Also, the radii of the corners 942 and 943 are r(ß), the same r(ß) of the truss hole minor vertices. In Fig. 79a and 79b, it can be discerned that the accessory 940 is constrained in the truss holes; no translation or rotation (in the plane of the figure) is free to occur.

Fig. 81 shows an accessory 950 with v-shaped plugs in parallel trussed wall sections 900d and 900e. Each plug is identical to plug 951a which has a rounded vertex 952a of radius r^* determined by Equation (1). The accessory 950 would not be properly constrained if only plugged into one trussed wall segment (e.g. 900d or 900e alone), but when engaged with both trussed sections, it will not be able to translate or rotate (in the plane of the figure). Notice that the accessory 950 can be rotated 180° and fit identically as is shown in Fig. 81.

Fig. 82, as still a further example, shows an accessory 960 having four sets of v-plugs in a square structure 955 having four sets of truss holes. V-plugs 951c and 951d are repeated on each side of the accessory. Given the radius design by Eqn. (1), the accessory can be rotated by any multiple of 90° and fit identically to that shown in Fig. 82.

In Fig. 83, two corner plugs 941c and 941d and one v-plug 951e fit in truss hole 940f. In truss hole 904g, two corner plugs 941e and 941f and one square plug 920g fit without interference in the truss hole. It should also be evident that the two sets of plugs can be moved laterally one truss hole and still fit without interference. Thus, accessories employing different types of plugs can be used in the same truss section as long as there is no interference in the other dimensions. This condition is realizable, as the following accessory designs demonstrate.

Fig. 84 shows two storage-"cubbies" 1000a and 1000b made of 90° axisymmetric structural elements 1001a-g. In the left storage-"cubby" 1000a, dividers 1010b, 1020b, 1030b and 1030c span the space 1002a vertically, while in the right storage-cubby 1000b, the dividers 11030d, 1030e, 1010c and 1020c span the hole space 1002b horizontally. It should be noticed that dividers are identical 1010b and 1010c, as is divider 1020b to 1020c, as are dividers 1030b, 1030c, 1030e and 1030f. These dividers can be moved along the sides of the storage-"cubbies" at truss-hole increments.

Fig. 85 shows the divider type 1010 alone. It has a wall component 1011 and two identical ends 1012a and 1012b. Fig. 86 shows close-ups of the ends of the three divider types depicted in Fig. 84. For divider 1010a, the end 1012c attached to wall component 1011a has a backbone piece 1015 with corner plugs 1013a and 1014a, like those of Figs. 79 and 80. Divider 1020a has two wall components 1011b and 1011c attached to the end 1022, identical to end 1012c of divider 1010a. Similarly, divider 1020a has an off-center wall component 1011d with end 1032, the same as ends 1012c and 1022. Other dividers can be made with different wall component configuration and with ends with different numbers of corner plugs at different separations.

These dividers of Figs. 84-86 slide into the truss sections as shown in Fig. 87. Wall component 1041 of divider 1040 slides under the lower wall thickness 1046 of truss section 1045, while plug 1043 slides into the truss hole above wall thickness 1046 which fills in the gap 1044 of the divider end 1042.

While the divider is constrained at the front of a cubby hole, the leading edge of the divider is thus far not constrained. Hence, a constraining tab, shown in front and side views Fig. 88 can be used. Constraining tab 1050 has lateral limit tabs 1053a, 1053b, 1054a and 1054b, corner plugs 1051a and 1051b as described with Figs. 79 and 80, a backbone component 1052, forming a gap 1055. As shown in Fig. 89, as divider 1040a slides into the trussed element 1045a, with divider wall component 1041a, gap 1044a and plug 1043a mating with truss wall thickness 1046a, the divider also mates with constraining tab 1050a. Divider wall component 1041a slides between the lateral limit tabs 1053cd and 1054cd. The constraining tab 1050a is attached to the trussed section as shown: corner tabs 1051cd and lateral limit tabs 1053cd and 1054cd are above and below, respectively, the truss wall thickness 1046a.

These dividers can also serve as drawer guides. Snap-on guide rails may also be added. Either vertical or horizontal drawers can be inserted into the subdivided storage-cubbies.

Plug-over accessories can be used with dividers and drawers. Accessories with rounded square plugs as briefly described with Figs. 77, 78 and 83, can take the form of an orthogonal connector, as shown in Fig. 90. The accessory 1060 has plugs 1063 to insert into truss holes as depicted in Fig. 77 and 78. Cut-outs 1065 provide volume clearance for other accessories such as divider end backbone components as shown in Fig. 91. The orthogonal plug in Fig. 85 is shown with the 90° axisymmetric barbed design with male barb 1062 and female mate 1061 in an orthogonal direction to the direction of the plug axes of symmetry.

Fig. 91 shows orthogonal plug 1060a being inserted into a trussed wall section 1045b over a divider 1040b. Note that clearance area 1065a of the plug is shaped so as to fit over the backbone component 1042b of the divider.

The orthogonal plug-in 1060b of Fig. 92 in truss wall section 1045c thus provides a means of attaching 90° axisymmetric wall elements described with Figs. 27-31 and 54-61 to an existing structure in a different orientation axis. Fig. 92 shows in particular a wall element 1100 and two terminator elements 1110a and 1110b completing a joint with the orthogonal plug 1060b. Obviously any one of the added elements can be interchanged with any element having the appropriate joint end.

The orthogonal plug, where desired, can also feature joint ends of any other geometry as well. Figs. 93a-c depict the orthogonal plug-in with the same plug shape 1063a, 1063b and 1063c, but with three types of joint ends: 90° axisymmetric end 1066; 45° axisymmetric joint end 1067; symmetric single male barb end 1068. The joint end may also be the round dogbone style of Figs. 17-20 as well as any other type of design.

The invention also enables other components to be attached to the orthogonal plug-in having the appropriate joint end. For example, Fig. 94 shows a door attachment 1070 with axisymmetric barbed joint ends 1071a and 1071b attached to orthogonal plug-ins 1060a and 1060b respectively. The door accessory end has the barb 1073a and barb mate 1072a required to interface with any similar axisymmetric joint end. The door accessory also has shafts 1074a and 1074b that allow the rotation of door component 1075 with respect to the ends 1071a and 1071b. Note that the shaft may be fixed with respect to either the door component or the joint ends. Fig. 95 shows views of the front and along the shaft axis of a door accessory 1070a. The joint end 1071c is seen mated with orthogonal plug-in 1060e, and door component 1075a is fitted to shaft 1074c.

A proper design for this door accessory should not interfere with other accessories of a structure. For example, Fig. 96 shows how this door accessory 1070b is joined with plug-in 1060e which can slide into trussed wall section 1045d over an existing divider 1040c. In this configuration, the divider is now captured in place; removal of the divider requires the removal of the door accessory 1070b.

A door that allows for the independent attachment and detachment of a divider or similar accessory is shown in Fig. 97. Here a door accessory 1080 is a plug-in assembly not having any joint end features, only the v-plugs 1085 (1085a-c in the front view with hidden lines). The door accessory has plugs 1085 attached to plug-in end 1081. The door component 1083 and shaft 1082 allow the door component to swing as desired. Also, from the front view, the plug-in end 1081 has clearance voids 1084a and 1084b. As shown in Fig. 98, the voids 1085d and 1085e on plug-in end 1081a can accommodate the corner plugs 1013a and 1014a on divider 1010d. Thus, the divider and the plug-in door accessory can be attached and removed independently of one another.

This independence of insertion is maintained regardless of what attachments have been made on adjacent storage-"cubbies". Fig. 99 shows the side view of two storage-cubbies 1002c and 1002d. The lower storage-"cubby" 1002d has a divider 1040e slipped into trussed wall section 1045e and plug-in door accessory 1080b already in place. Storage-"cubby" 1002c already has divider 1040d inserted into trussed wall sections 1045d and 1045e. The additional plug-in door accessory 1080a has plug-in ends 1081b and 1081c (and plugs 1085d and 1085e). These plugs can thus be inserted into wall sections 1045d and 1045e over the divider 1040d without interference from any accessory. If the door component is swung out, exposing the storage-cubby, then dividers can be removed and inserted, as Fig. 98 has illustrated.

Another accessory is the plug-in plate of Fig 100. This backplate 1090 has the plate component 1092, which can be solid or with holes to reduce weight and material, and a cavity 1093. It also has v-plugs depicted as 1091a-c. Fig. 101 shows that plug-in backplate 1090a can be attached to a structure with plugs 1091d fitting into a trussed wall section 1045f over an existing lateral constraining tab 1050a already in place. The constraining tab 1093a would be in the cavity 1093a of the plug-in backplate. If for some reason a divider were inserted from this direction instead of the lateral constraining tab, then backplate would also fit over it. Fig. 102 shows that a constraining tab 1050b can also be inserted after a plug-in backplate 1090b has been added to trussed wall section 1045g. The tab 1050b is pushed back into the cavity 1093b without interfering with backplate component 1092a and then forward to engage the trussed wall section 1045g. Obviously, the tab can be removed independently from the backplate plug-in accessory.

Other accessories can also be employed. Fig. 103 shows an extender for the 90° axisymmetric joint end. In applications where a given wall element is not long enough, the extender 1100 can be fitted to the end of the element. It has reversed barb 1102 and reversed barb mate 1101 to join with a standard axisymmetric joint end, and also the standard barb 1104 and barb mate 1103. Fig. 104 shows a possible application of these extenders: extenders 1100a and 1100b are used in tandem to extend wall elements 1002h and 1002j respectively, to join with perpendicular wall element 1002i. The concept of an extender can also be used for joint ends of different geometries. Fig. 105 shows an extender 1110 for the single male barb joint end. This is not, however, the same as the connector for the single male barb end as shown in Fig. 47.

Fig. 106 shows how the 45° axisymmetric end elements 1200a and 1200b can interlock without forming the 45° inter-element angle. This is generally not desirable, since the strength of the joint is significantly weaker than a complete interlocking joints of Figs. 37, 39 and 41. Fig. 107 shows how the 90° axisymmetric elements 1210a and 1210b can similarly be interlocked without forming the 90° angle. In storage applications, these joints can be potentially dangerous as the failure of a joint can lead to falling objects upon person or property. To prevent this, end features having asymmetric (not symmetric) barb features can be used. Fig. 108 shows the end of an element 1220 having one barb 1224 and one barb mate 1221. The opposite end of element 1220 would have the same features axisymmetrically oriented, so that a rotation of 180° results in the identical element ends, as are the previously described elements in Figs. 27-31 and Figs. 54-61. A close-up of element 1220 is shown in Fig. 109. The barb 1224 has barb head ends 1225 and 1226 that are dissimilar. In this example, barb head end 12256 has extra material as compared to barb head end 1225. Similarly, the geometry of the barb mate 1221 has vacancy 1222 different from vacancy 1223. The shape of barb head end 1226 is the same as barb mate vacancy 1223 while the barb head end 1225 has the same shape as vacancy 1222.

Fig. 110 shows two axisymmetric end elements 1220a and 1220b having asymmetric barb features. The dissimilar barb head features will not allow the barb to interlock in the barb mate as is possible with symmetric barb features in Figs. 106 and 107 in this relative orientation of elements. For example, barb 1224a on element 1220a will not join with barb mate 1221b of element 1220b because the larger barb head end 1226a will not fit into the barb mate vacancy 1222b. Fig. 111 shows that the desired joint can still be formed with the axisymmetric elements with asymmetric barb features of Figs. 108 and 109. Four elements 1220c, 1220d, 1220e, and 1220f interlock to complete the joint.

Up until now, the wall elements and plug-ins herein described have all been orthogonal in nature. That is, the axes of joining elements have been designed for 45° and 90° intermember angles. This is not a fixed requirement, however, or a limitation of the invention. The end clips and plug-ins can be made to employ an angle other than 45° or 90° between the axis of attachment and the direction of mating attached elements. For example, the plug-in door accessories of Figs. 94 and 97 can have door components swinging on an axis at angles other than 90° from the plugs' insertion direction by forming the plugs at that desired angle with respect to the door direction. Similarly, end clips, such as those of Figs. 50-62, can have the joint ends at an angle with respect to the centerline of the jaw components.

Also, the wall elements themselves can be cut at angles. Whereas for much of this invention description and for substantive purposes the storage-"cubbies" may have been assumed to be cubical in shape with 90° at every edge, the storage-"cubby" volumes may also be formed with non-perpendicular angles such as rhombohedral or some non-equiangular geometry. The joint ends and wall components need only be cut off-axis from the direction of joint sliding direction. The cross-section design need not be changed, as the direction of the sliding joint will always be maintained. Thus angled shelves can also be made.

The designs of the invention can be applied, moreover, to many modular design applications including but not limited to the above-described bookshelves, storage racks, modular office furnishings, home furnishings, semi-permanent housing shelters and structures, ceiling paneling, floor and wall paneling, lockers, and carrying cases and the like. The elements, as earlier described, can be made of plastics, metals, composites or practically any other material (or combination of materials) that has (have) appropriate material properties for the given application. While many of the embodiments described herein are most easily made by extrusion and injection molding, moreover, other manufacturing processes may also be used.

Suitable tools can be readily designed especially for the custom-fitting of the embodiments of the invention described above. A shearing tool can be designed, for example, such that the end clips and core elements can be cut at any angle required to make equiangular or non-equiangular storage-"cubby" systems. Material lengths, such as a long plastic extruded end clip strip, can be placed in a mating die tool, and a hand-operated shear can cut off the desired length without deforming either portion of the extruded strip. This device can be designed with a rotational adjustment between the shearing surface and the material so that angular cuts can be consistently and repeatably made. Similarly, the tools may also include a punch so that as the shear is brought down to cut off the desired section of an end clip strip, for example, a punch can make a hole in the jaw walls for screw installation during the same action. This device can also be motorized or pneumatically-driven to ease operation as is well known.

For the attachment of protruding-jaw-tooth end clips, an installation tool can be made to simplify the mating of the end clip onto the end of a board or wall component. The tool holds the end clip in place and prevents the jaw walls from spreading, and the wall component is pressed into the end clip in either the direction of the sliding joint axis or in the direction from the jaw gap towards the joint end. This force may be provided by either a hammer-like device where impacts force the two components together or by a press with a lever, like an arbor press. Once the two components are pressed together, the assembly is then removed from the tool, ready for joining with other such assemblies. The force may also be motorized or pneumatically-driven to increase installation rates with less user exertion.

While applications of the invention to many structures, including "cubbies" and toys are readily understandable, feasibility studies have been conducted that also admirably support the use of the structures of the invention in heavy load-bearing applications, as well, in competition with current construction designs for such uses.

A truss cross-section in wall components is generally known to provide a greater strength-to-weight ratio than solid sections. A study using finite element analysis (FEA) has been conducted to compare trussed beams to I-beams ("Structural analysis comparison of a square-hole beam and a triangular-hole beam" by Luis A. Muller of the Precision Engineering Research Group, Dept. of Mechanical Engineering, MIT. October

1995). A triangular-holed truss shown in Fig. 112a and a rectangular-holed truss of Fig. 112b are compared to the stiffness of an I-beam.

Results of center loading on a simply supported beam 305mm long show that a triangular truss of 25mm overall height, 25mm depth, and 5.0mm wall thickness, is nearly 100% efficient as an I-beam of the same overall height, whereas a square-hole beam only performs to 73% efficiency.

Also, analytical models show that the stiffness of a beam with separated and parallel plate surfaces is more effective than a single wall component of the combined thickness. For example, a beam of two 5.0mm plates separated by 15mm (overall thickness 25mm), shown in cross-section in Fig. 113a, is 12.5 times as stiff as a single 10.0mm plate beam of Fig. 113b. This is the result of a higher moment of inertia provided by the separation of plate elements from the beam centerline.

Considering likely materials and dimensions of a structural wall element with barbed joint features, first-order calculations of bending, buckling and strength have been conducted to show the feasibility of the designs and embodiments described above. (Outlined in, for example, Housner, G and Hudson, D. Applied Mechanics: Statics, D. Van Nostrand Company, Inc., 1949, and Shigley, J and Mischke, C. Mechanical Engineering Design, McGraw-Hill, 1989.) Rigid polyvinyl chloride (rigid PVC) is a common engineering plastic which can also be recycled and reused. It typically has a modulus of elasticity in the E=200000 psi to 600000 psi range. (McClintock, F. and Argon, A. Mechanical Behavior of Materials, Addison-Wesley Publishing Co., 1965. Pg. 258 (Table 6.4 Properties of Common Polymers.) Commercially-available rigid PVC products ("Vinyl Siding Product Standards & Specifications," Georgia-Pacific product brochure, 1993) have a value of E=360000 psi. For the following calculations, a value of E=300000 psi is used.

Consider a trussed wall element with the following geometry: b=12" deep shelf; l=12.5" from joint-end to joint-end; overall element thickness H=0.75"; wall thickness h=.050". The moment of inertia I for separated plates is:

$$I = \frac{b}{12}\left[H^3 - \left(H - 2h\right)^3\right] \qquad (2)$$

For as simply-supported beam with center loading, the deflection y at the center, also the maximum deflection, is given by:

$$y = -\frac{Fl^3}{48EI} \qquad (3)$$

where F is the center load. Using the values given above, a load of F=400 lbs, for example, results in a maximum center deflection of only 0.37". In an array of structural cubbies, however, the ends of these beam-acting wall elements would be resistive to end rotation; hence the deflection would be less than this calculated value. Typical household objects weigh less than 400 pounds; thus, the deflection of the walls under distributed loading would be less than the example calculated value.

An array of storage cubbies containing objects would stress the bottom-most wall elements the most, as the weight of the upper storage cubbies would be carried by the bottom row of cubbies. Hence, first-order calculations for buckling of vertical column wall elements are conducted. The first mode of buckling gives the lowest critical load of:

$$P_{crit} = \frac{\pi^2 EI}{4l^2} \tag{4}$$

where P_{crit} is the load at which buckling will occur. For the given geometry of the wall element, the first mode of buckling has a critical load of P_{crit}=697 lbs. Also, since one storage "cubby" is composed of two vertical walls, the load would be shared by two vertical columns. Thus, the first buckling mode for a storage cubby would occur at twice the critical load calculated in Eqn. (4). Also, since the storage "cubby" is resistant against racking and diagonal forces at the joined ends, the storage structure could be capable of higher loading before failure.

The local wall segments within a truss have also been studied. A local wall segment that makes up the trussed wall element might buckle or fail, thereby weakening the entire wall element at a lower load than that calculated above. Hence, consider a thin wall column of l=1.4" tall, H=0.050" thick. The moment of inertia of this rectangular cross-section is:

$$I_{rect} = \frac{bH^3}{12} \tag{5}$$

From Eqns. (4) and (5), P_{crit} = 47 lbs. Again, this is conservative, as the truss structure distributes the load throughout the truss wall members in constrained ways. Also, for each cubby wall element, the load capability is higher than the calculated value because each trussed element has two thin wall panels acting as columns. Since the wall segments are more like pivoting-ends or partially slope-constrained columns, a more accurate buckling load can be calculated. For buckling of a column with pivoting-ends (free to rotate), the critical buckling load is:

$$P_{crit} = \frac{\pi^2 EI}{l^2} \qquad (6)$$

This results in a critical load of P_{crit} = 188 lbs. Again, the maximum load is significantly higher because there are two thin walls per cubby element, and each cubby has two vertical members (one on each side).

The strength of a single barb of Fig. 54, for example, is also considered. The strength of an element is given by:

$$P = wb\sigma \qquad (7)$$

where P is the failure load, and σ is the strength of the material. Rigid PVC has a typical tensile strength of T=6000 psi, but for safety considerations and creep behavior in plastics, a value of σ=1000 psi is used. Using a barb thickness of w=0.100″, Eqn. (7) results in a value of P=1200 lbs. For a thinner barb of w=0.080″, the failure load is P=960 lbs.

Applying Eqn. (7) to the trussed wall component, a thin wall segment of w=0.050″ results in a maximum load of P=600 lbs. A thinner wall of w=0.040″ gives P=480 lbs.

Thus, the first-order conservative calculations show that the structural properties of the trussed walls with barbed joint ends of the present invention can be made to withstand typical loads using a commonly-available, inexpensive, recyclable plastic.

In addition to the formation of storage cubes, the extruded truss-type plate elements can also be formed into the equivalent of lightweight boards as shown in Fig. 114. Here the truss structure 2000 has the same form as say element 1001b in Fig. 84; however, one edge 2001 may be concave, and the other edge 2002 may be convex and mateable with edge 2001. In this manner, several of the boards could actually be bonded together. This type of truss-type board would allow for much lighter-weight shelving.

There will also be cases where the advanced extrusion technology required to create wide truss-type sections can also be used to create replacements for boards used in applications like shelving. Fig. 115 shows a cross section that could be used for this purpose, although so could for example the cross section in Fig. 114. In Fig. 115, the truss-board 2005 has edges 2007 and 2006 which are rounded, but may be any shape pleasing to the eyes.

Further modifications of the invention will also occur to persons skilled in the art, and all such are deemed to fall within the spirit and scope of the invention as defined by the appended claims.

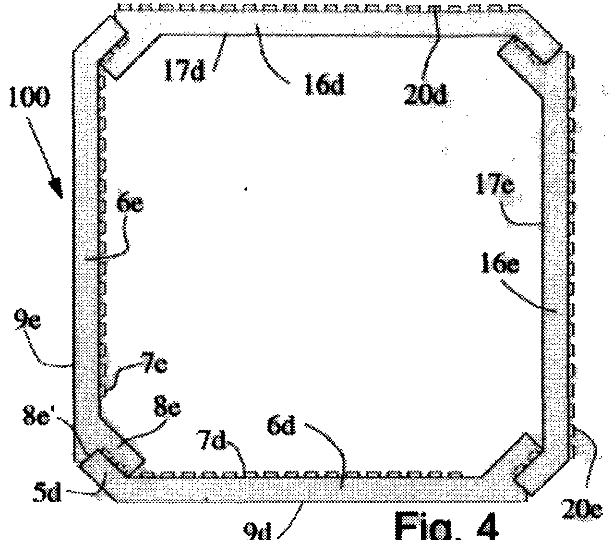


Fig. 4

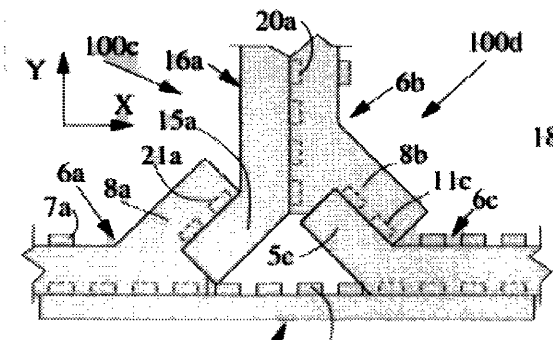


Fig. 5

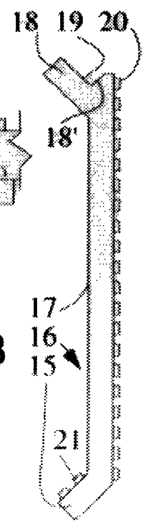
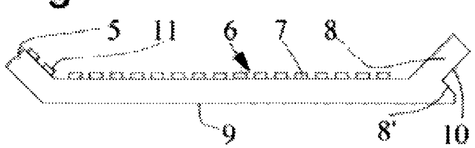


Fig. 3

Fig. 2



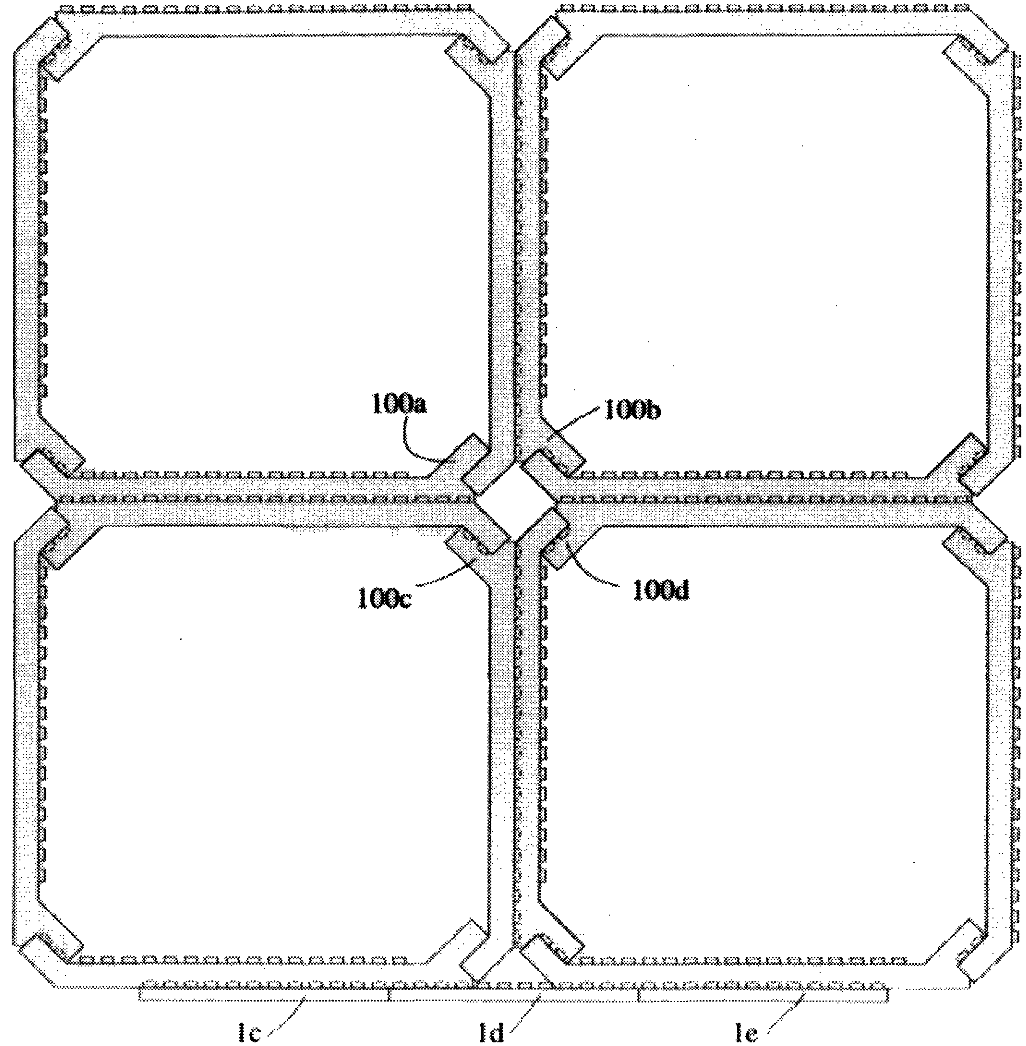


Fig. 6

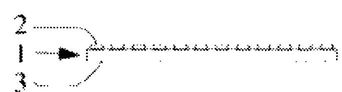


Fig. 1 (prior art)

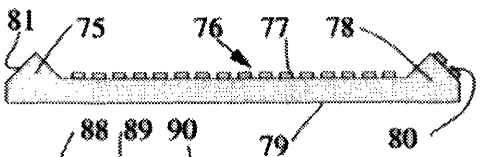


Fig. 7

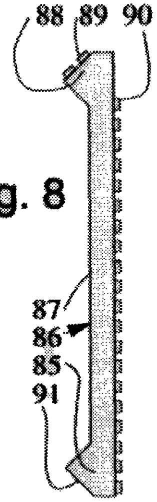


Fig. 8

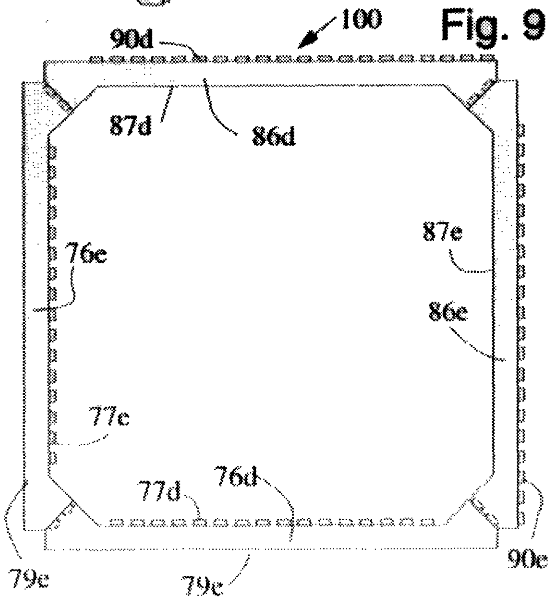


Fig. 9

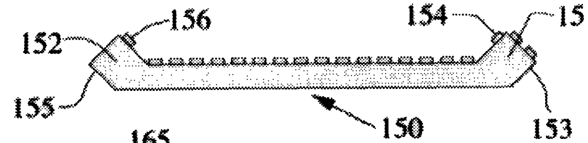


Fig. 10

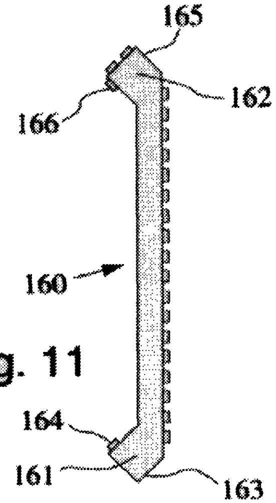


Fig. 11

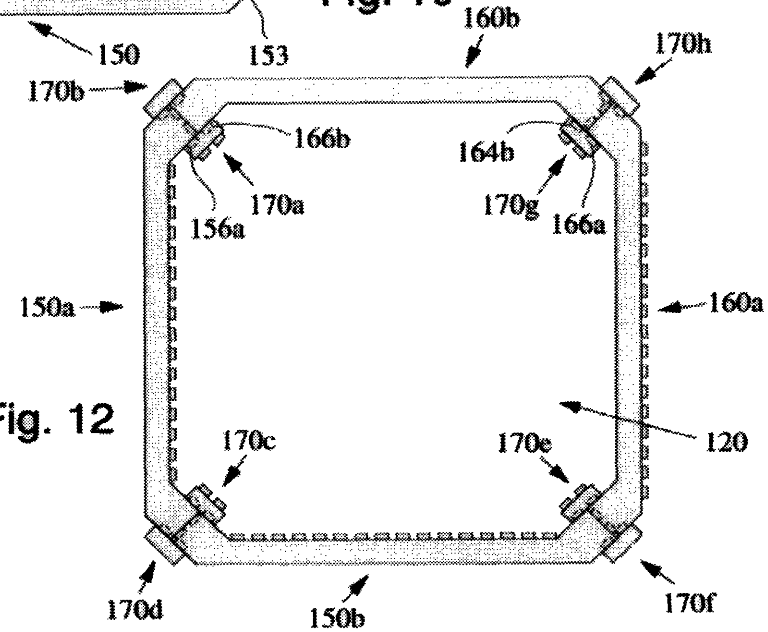


Fig. 12

Fig. 13

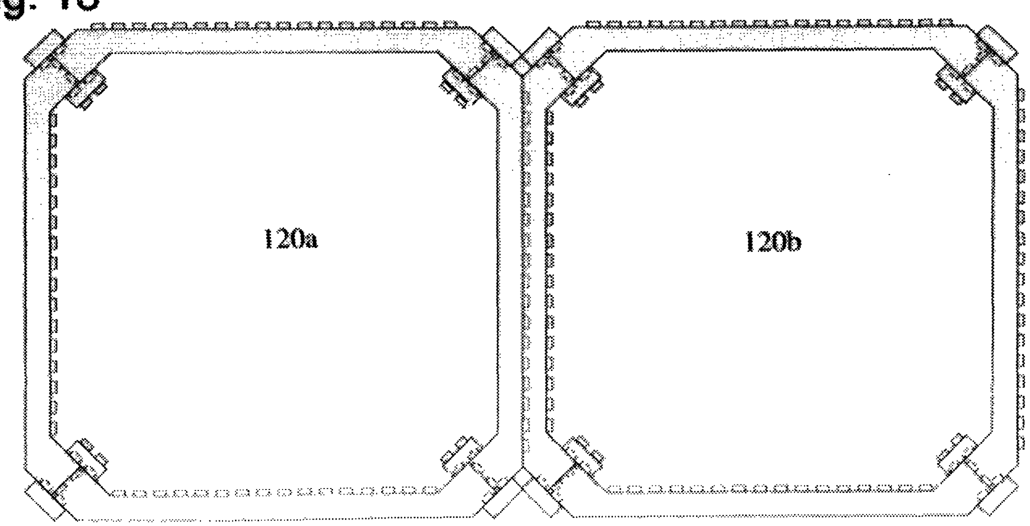


Fig.14

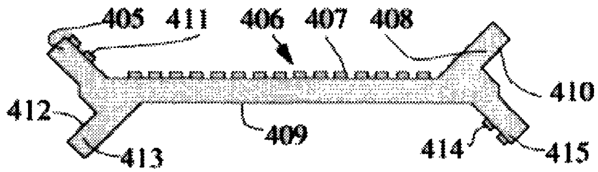


Fig.15

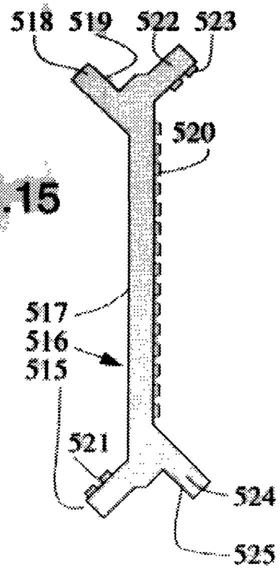
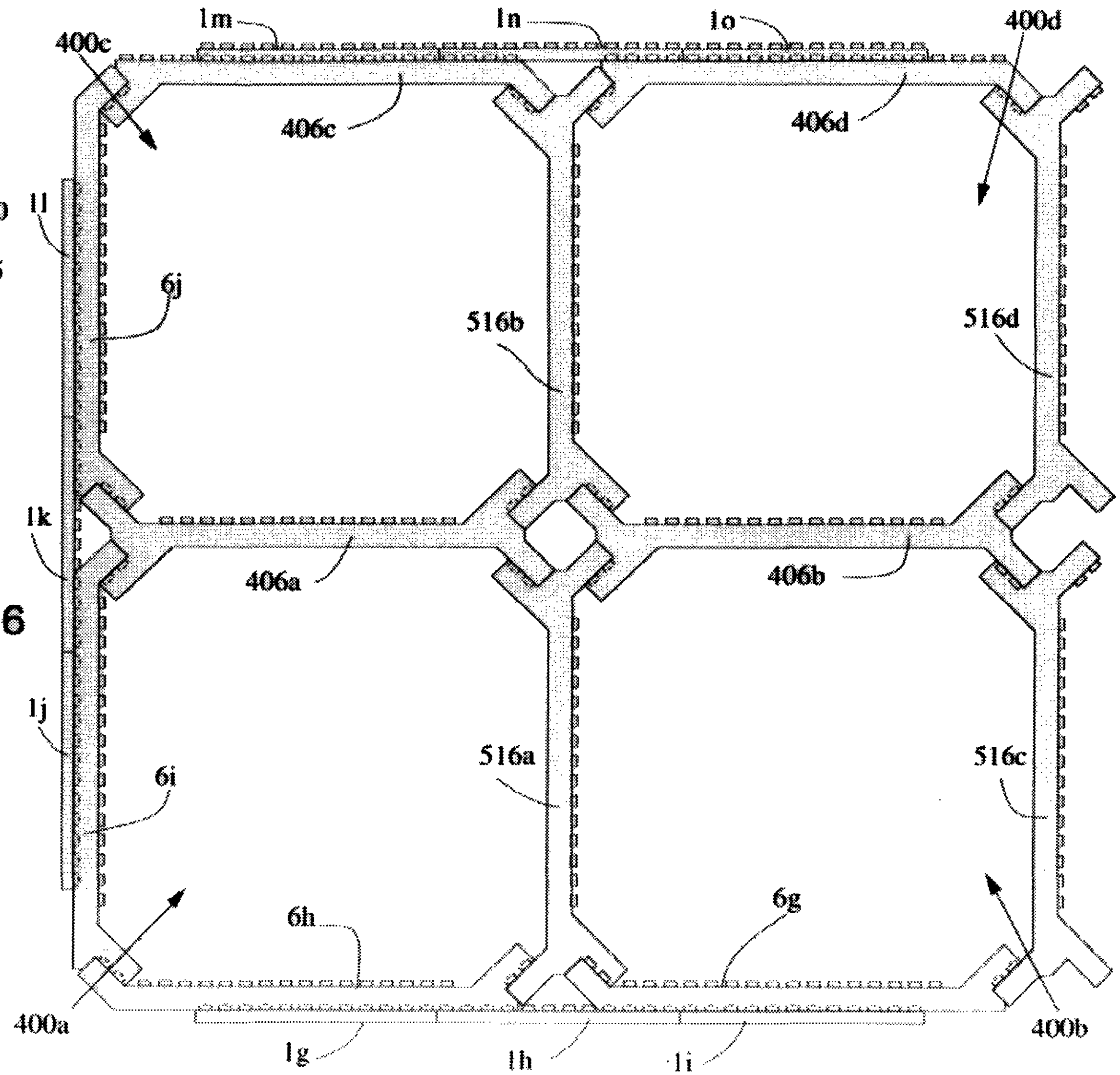


Fig.16



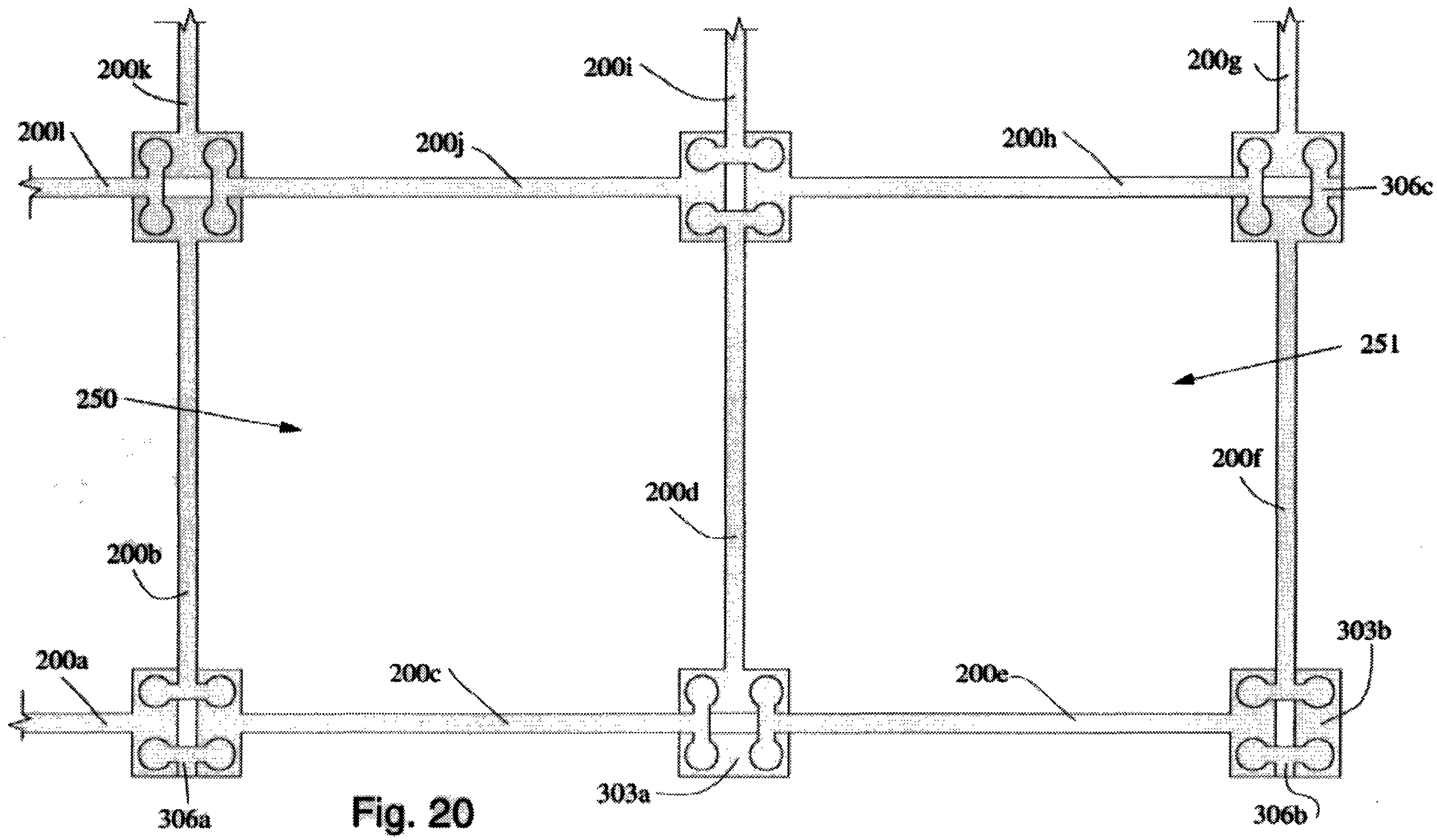


Fig. 20

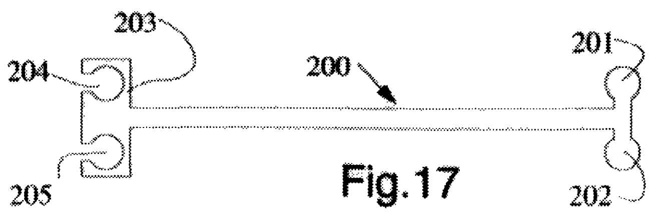


Fig.17

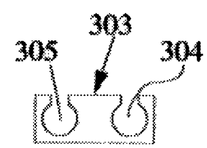


Fig.18

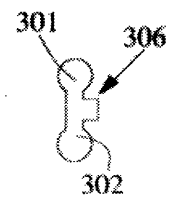


Fig.19

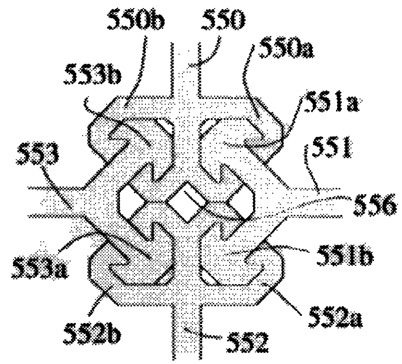


Fig. 25

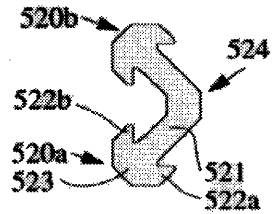


Fig. 23

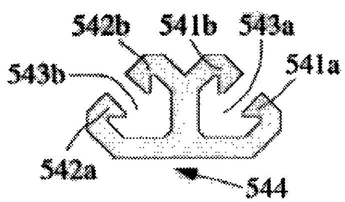


Fig. 22

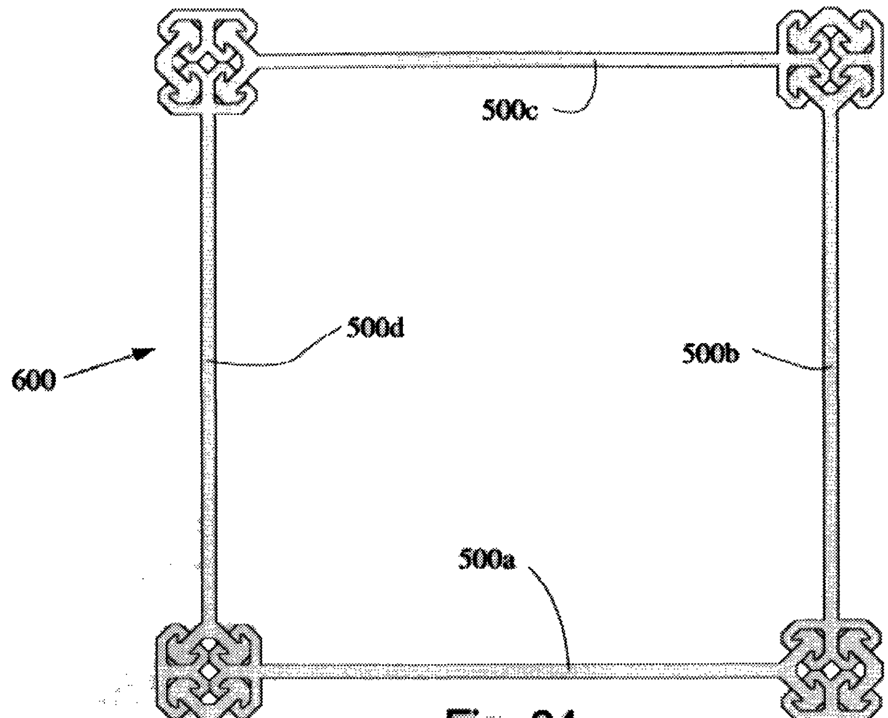


Fig. 24

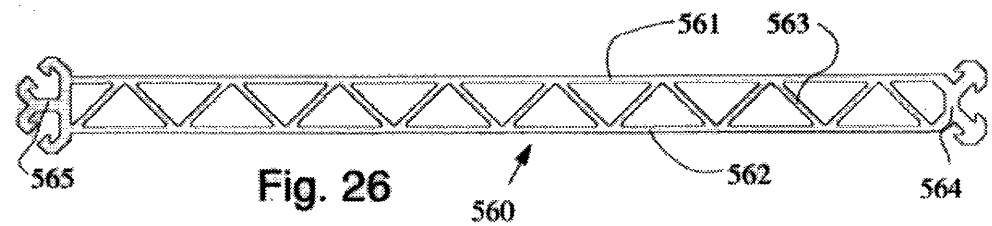


Fig. 26

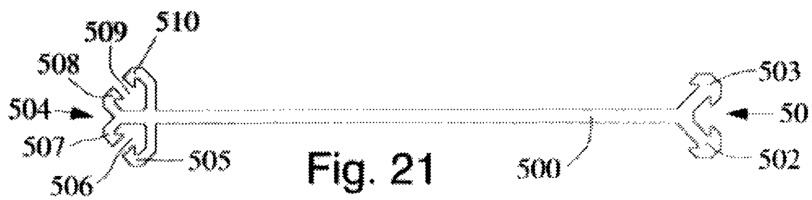


Fig. 21

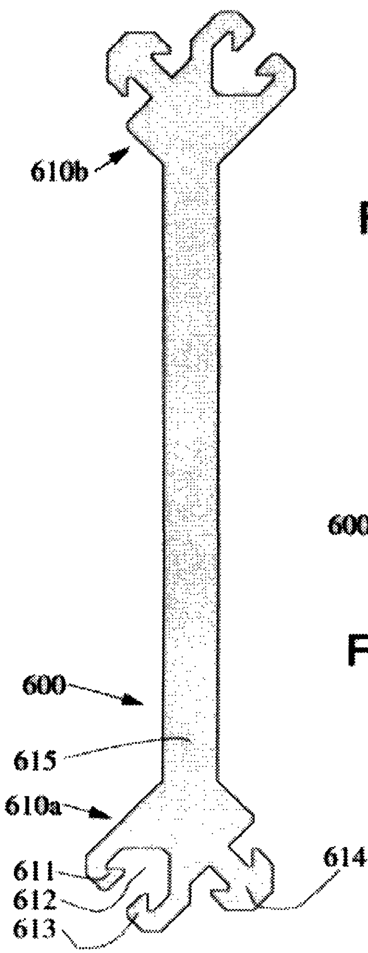


Fig. 27

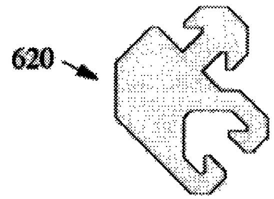


Fig. 29

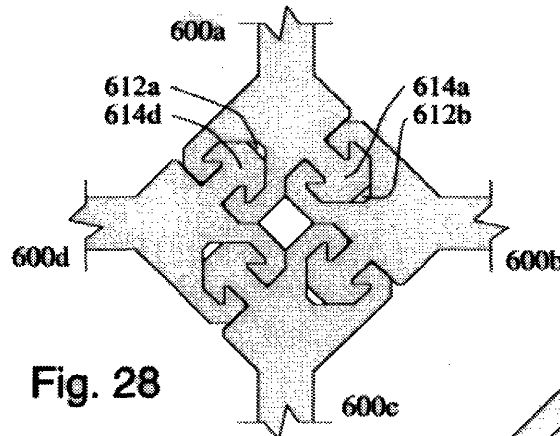


Fig. 28

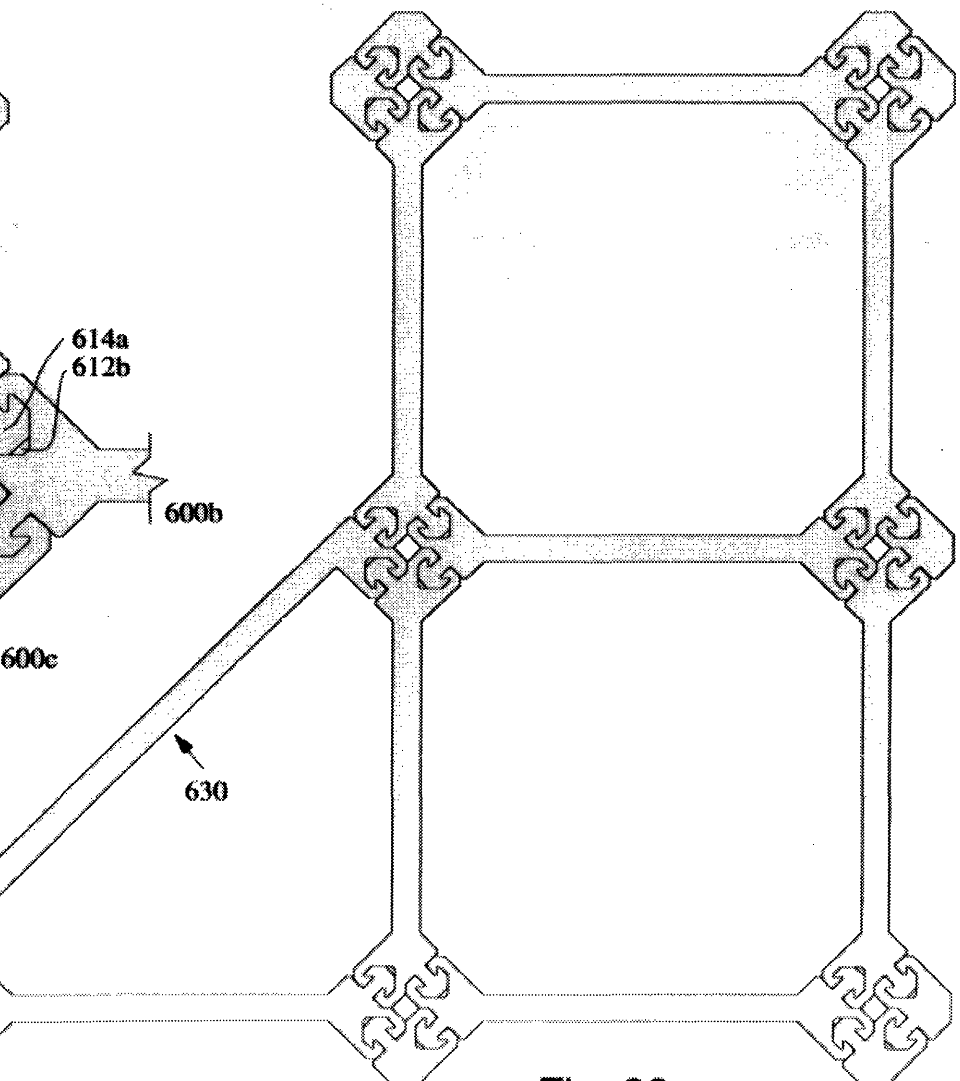


Fig. 30

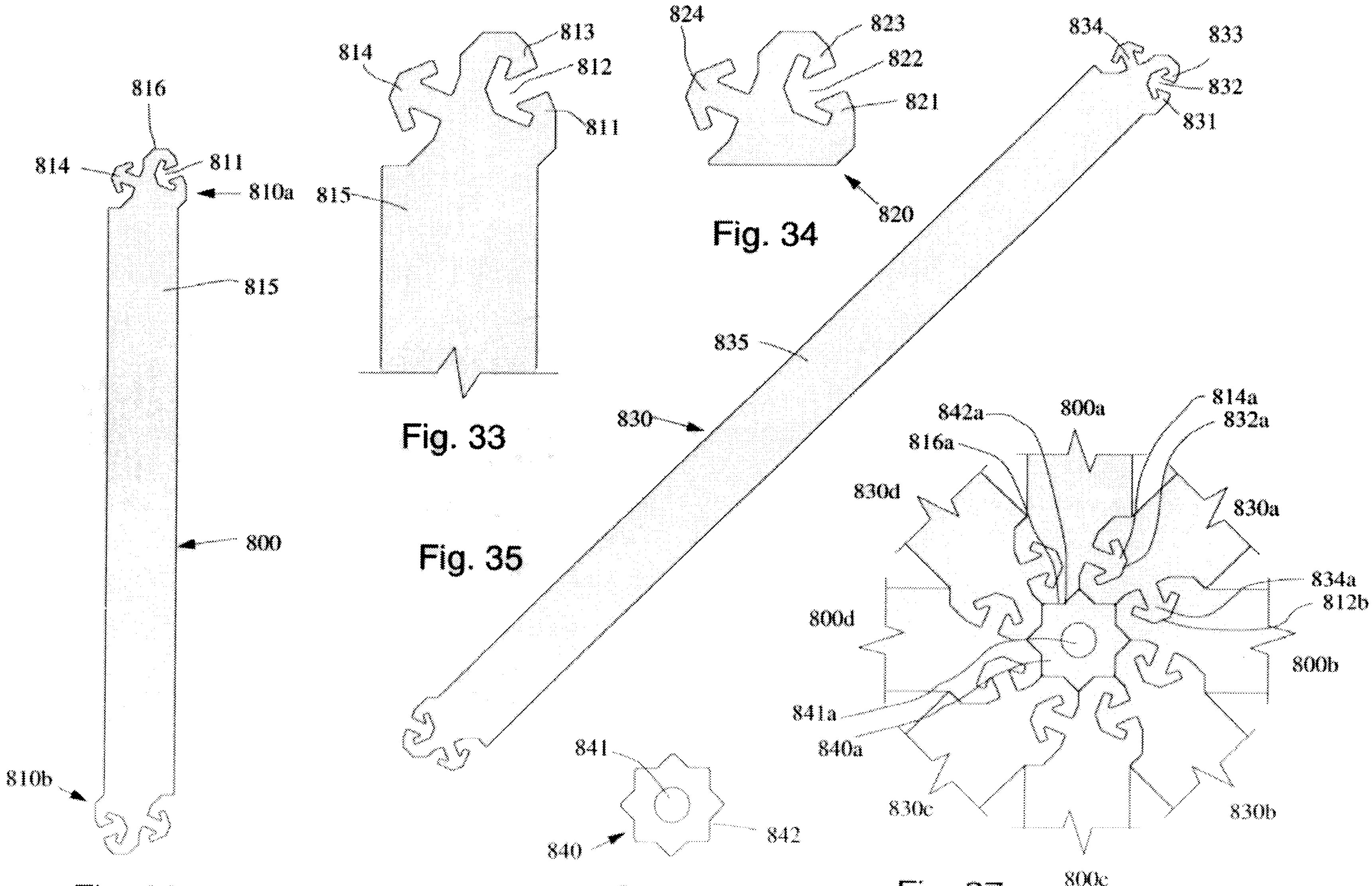


Fig. 32

Fig. 33

Fig. 34

Fig. 35

Fig. 36

Fig. 37

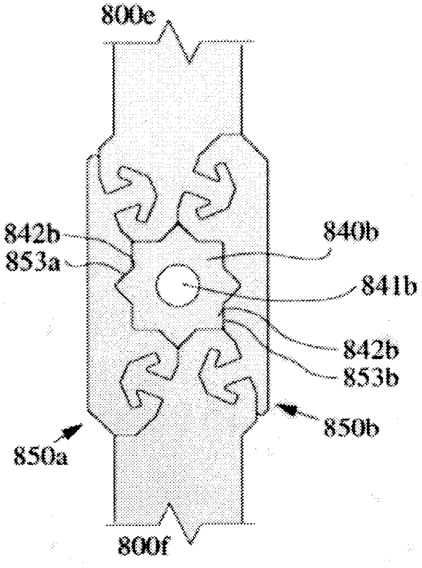


Fig. 39

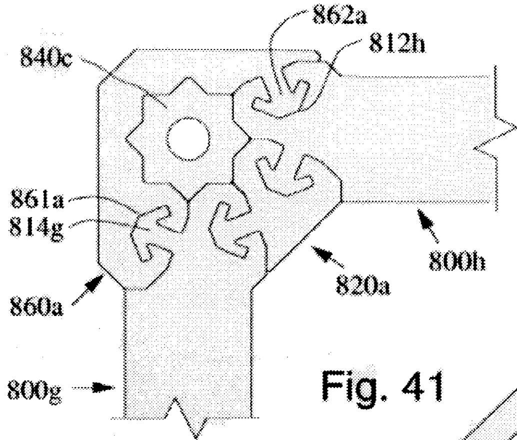


Fig. 41

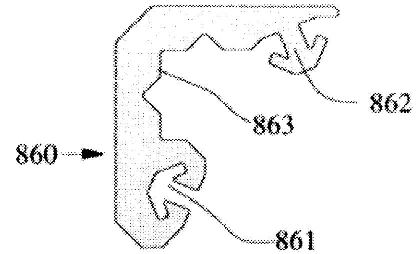


Fig. 40

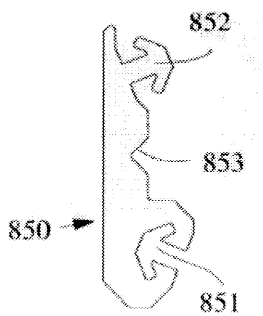


Fig. 38

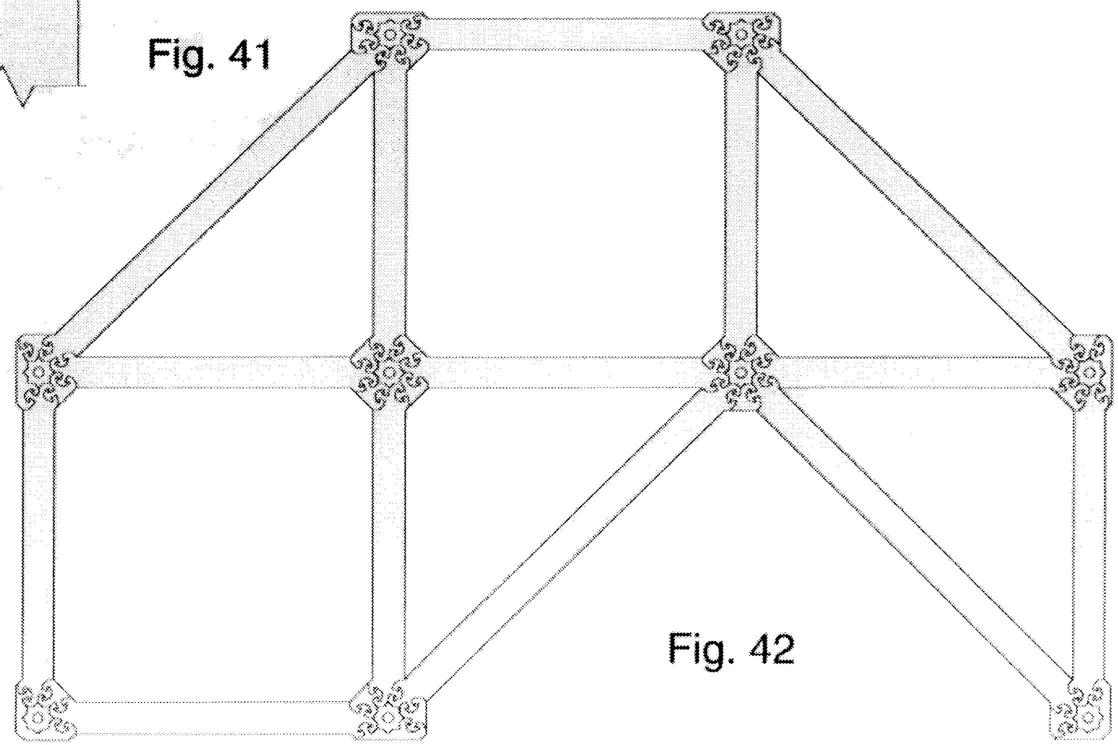
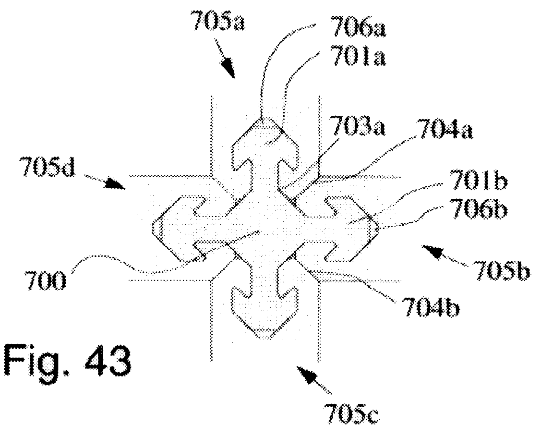


Fig. 42



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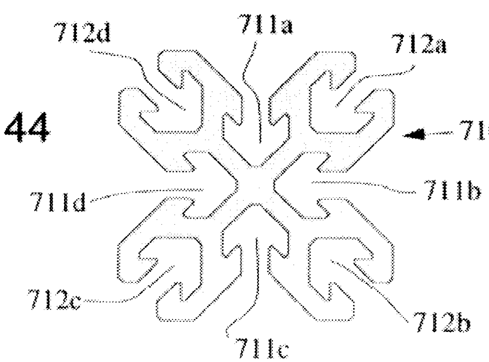


Fig. 44

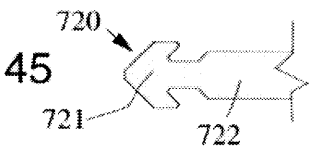


Fig. 45

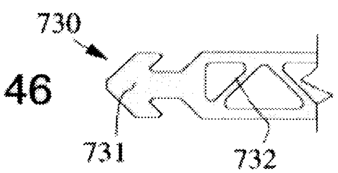


Fig. 46

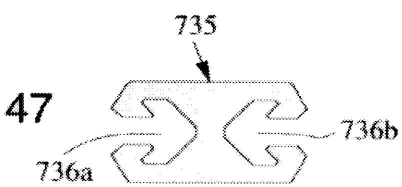


Fig. 47

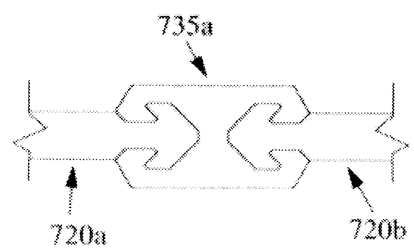


Fig. 48

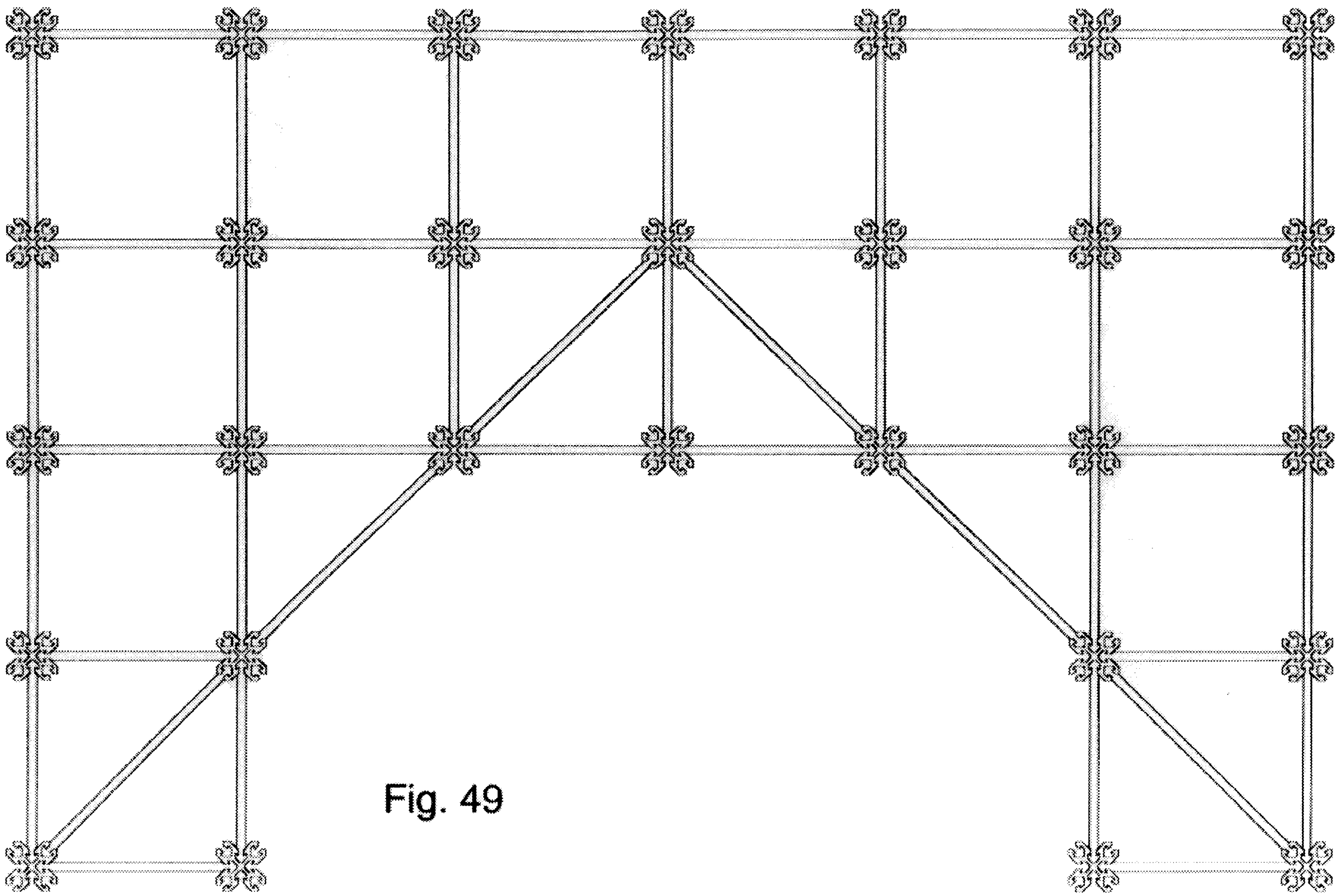


Fig. 49

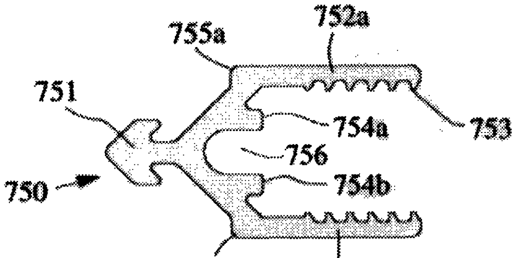


Fig. 50

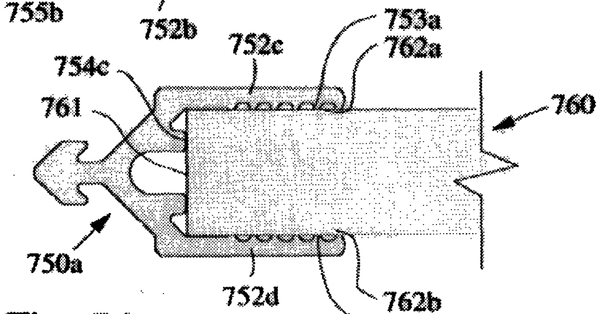


Fig. 51

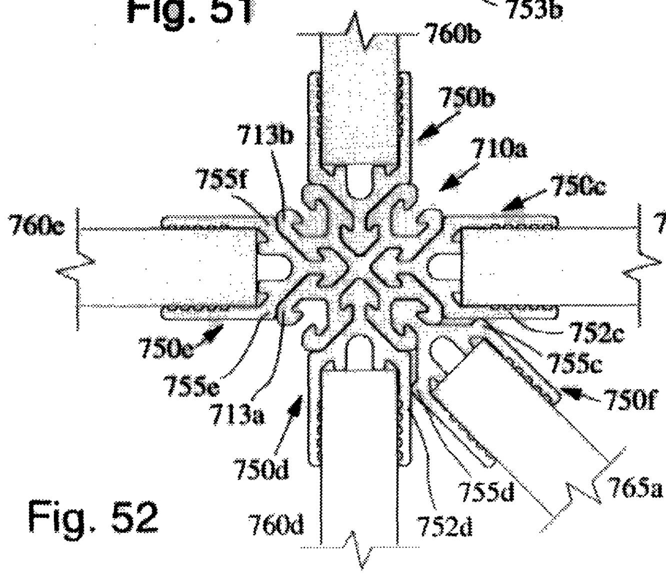


Fig. 52

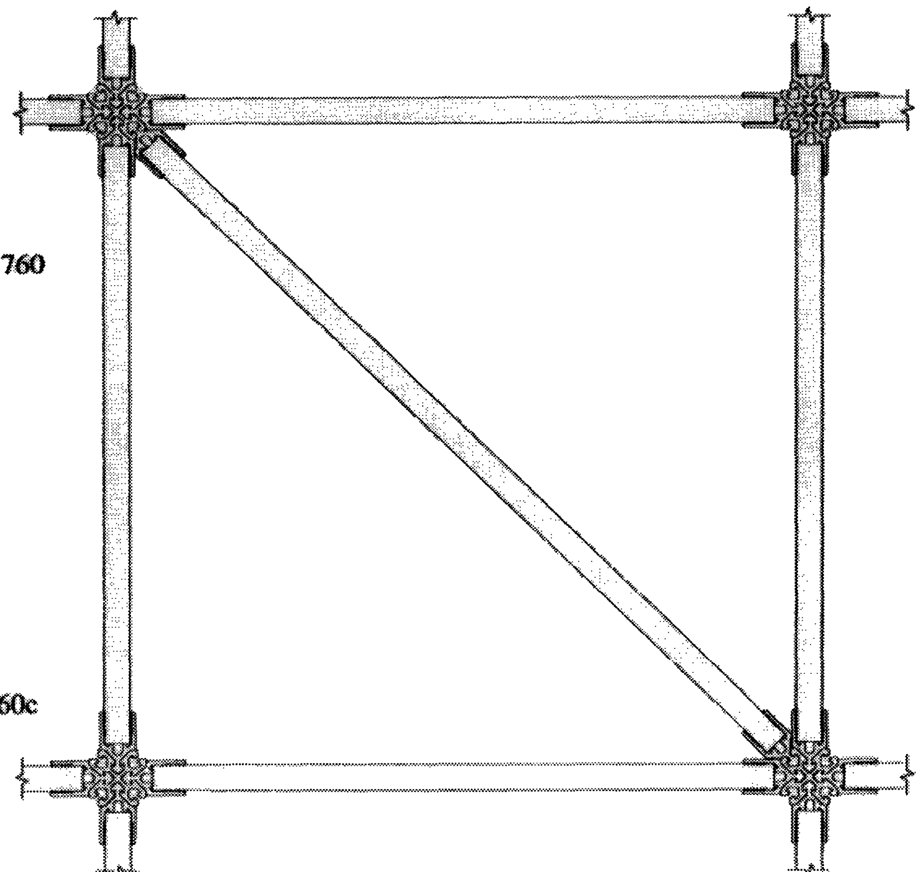


Fig. 53

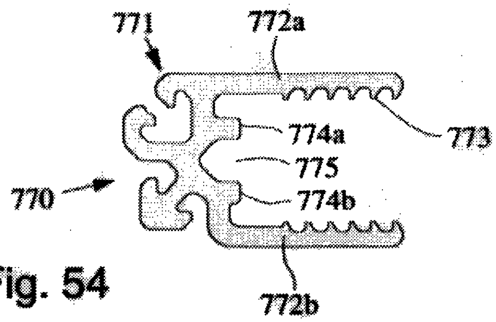


Fig. 54

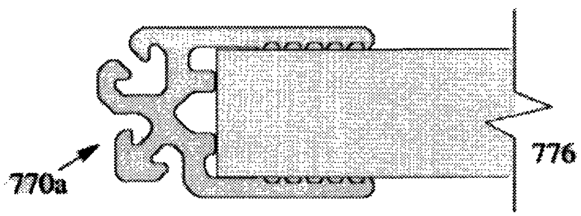
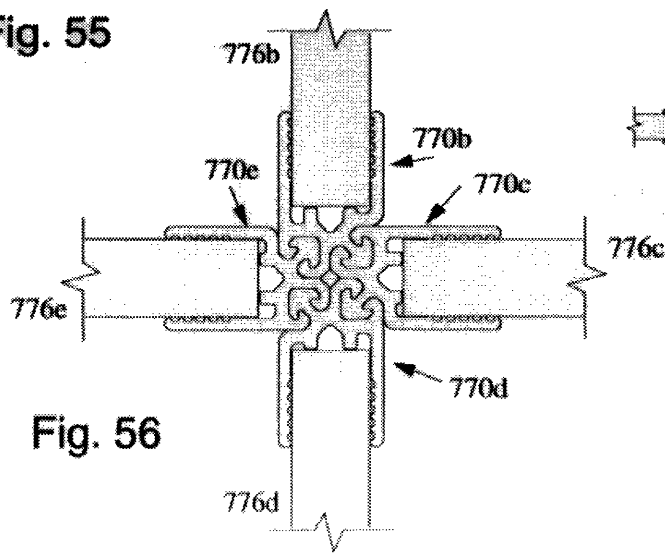


Fig. 55



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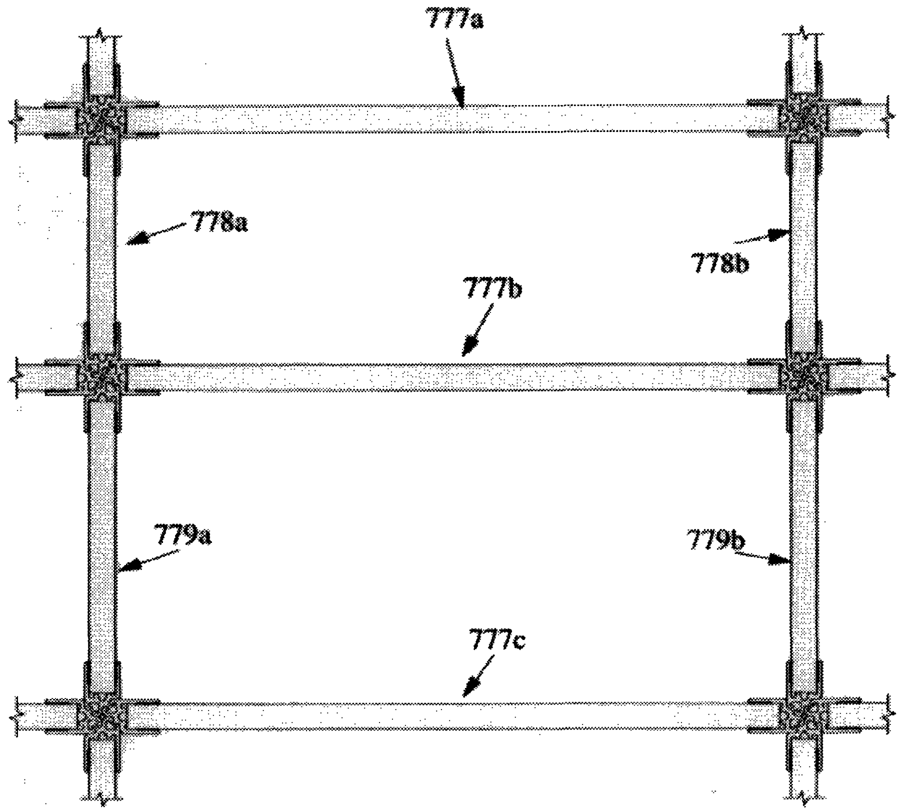


Fig. 57

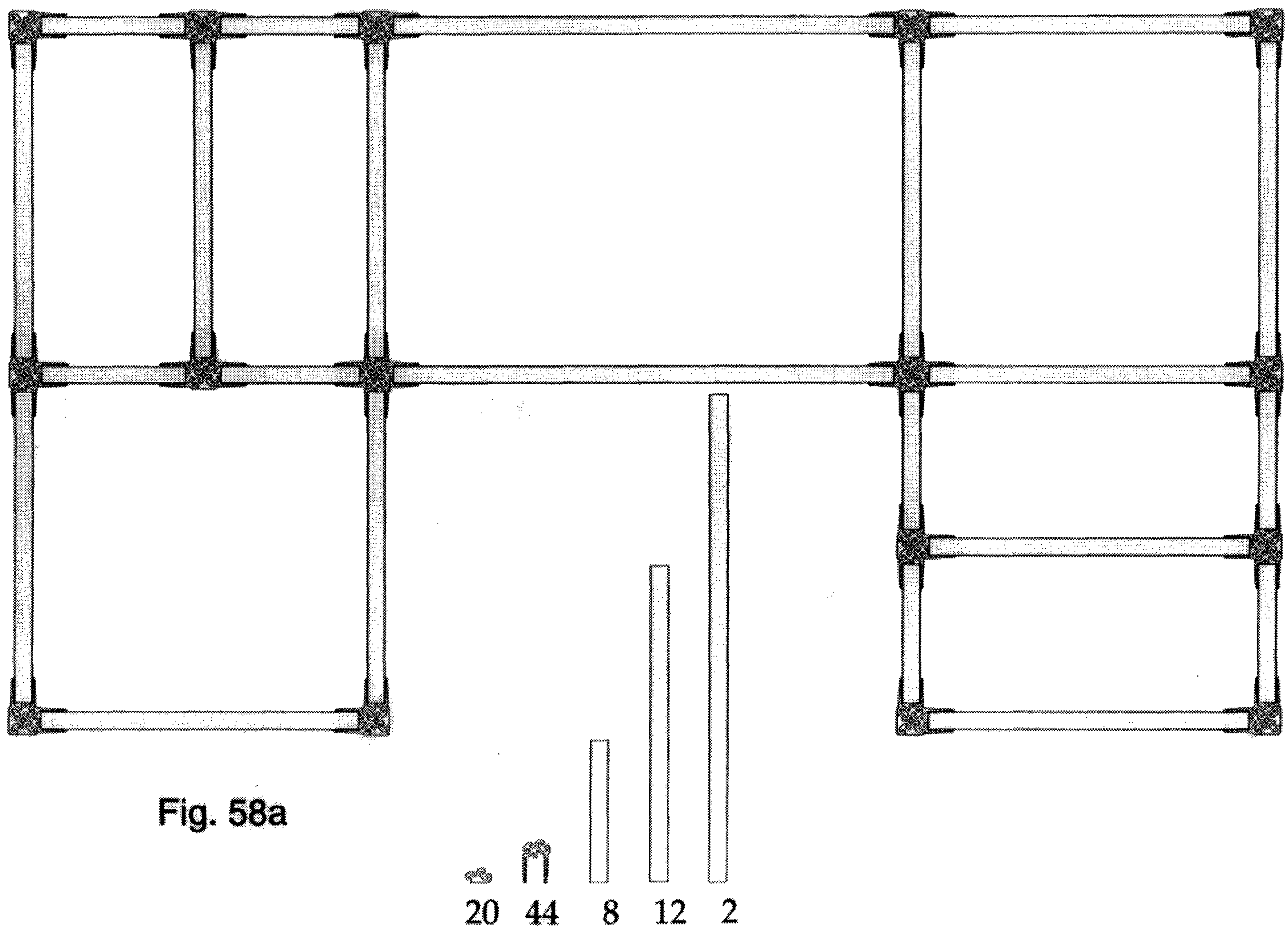


Fig. 58a

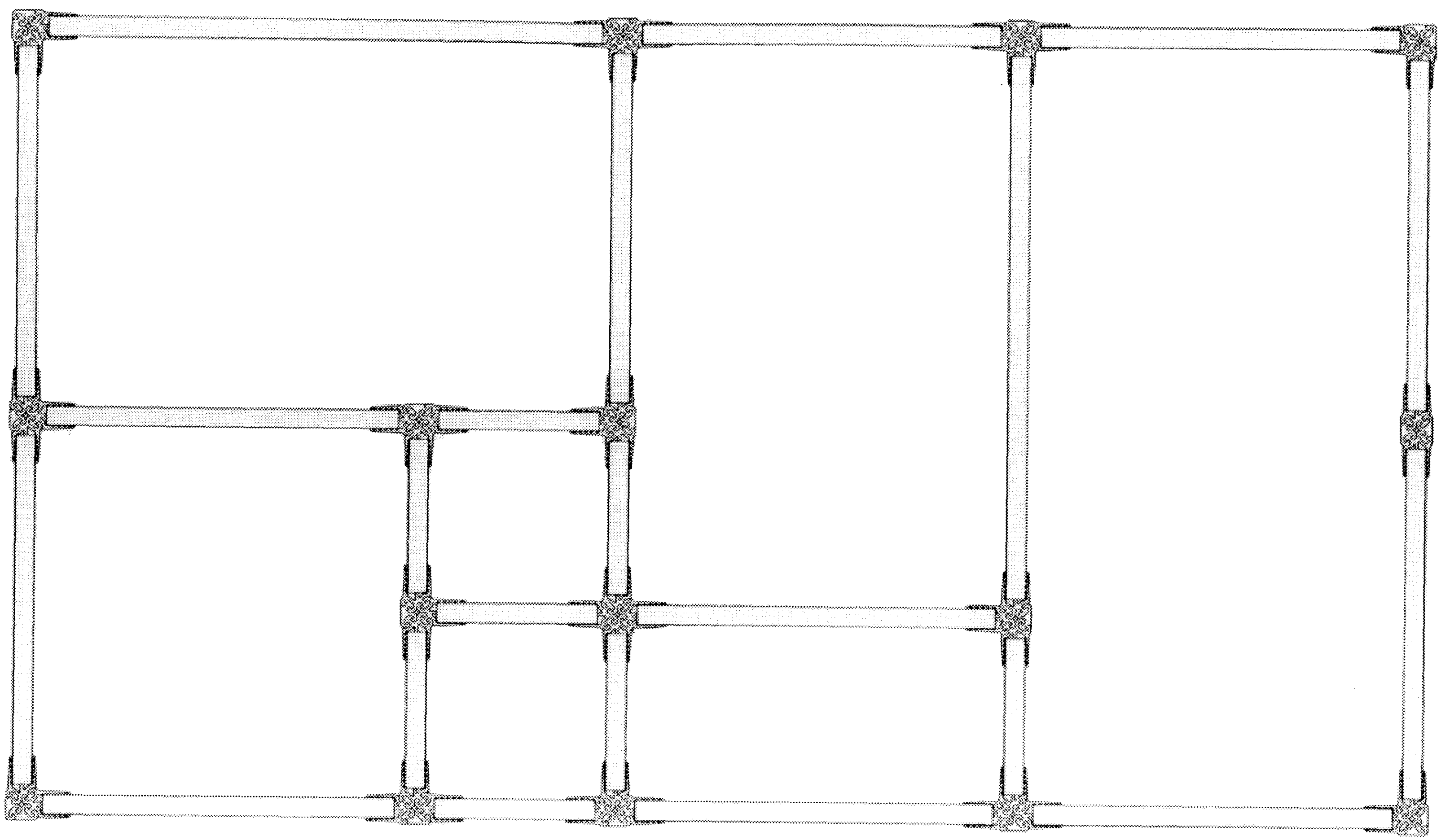


Fig. 58b

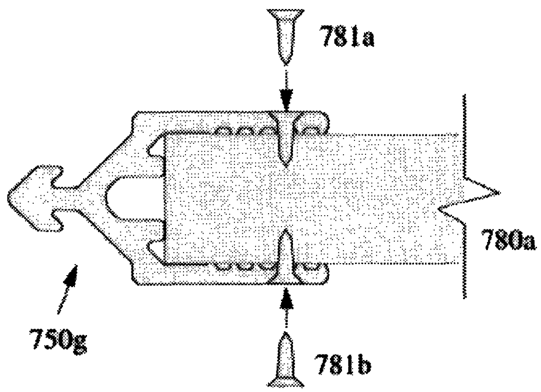


Fig. 59a

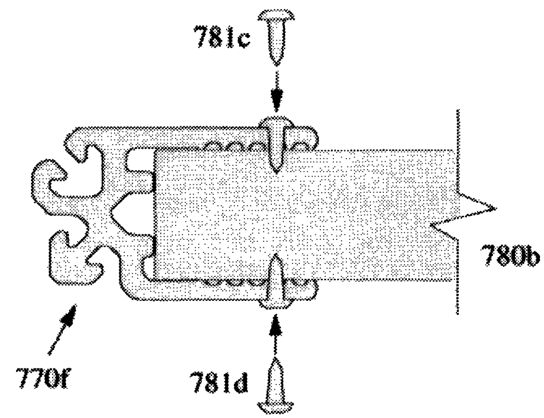


Fig. 59b

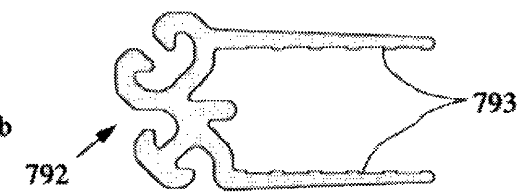


Fig. 60

Fig. 61a

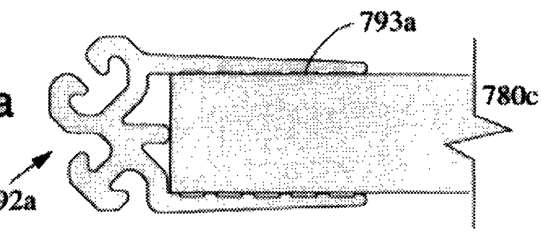


Fig. 61b

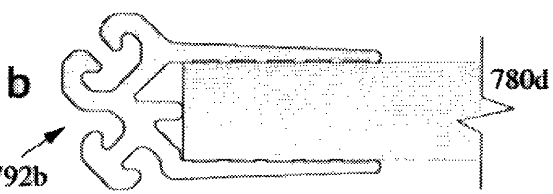


Fig. 61c

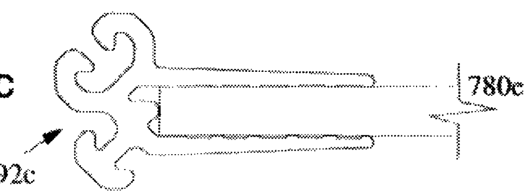
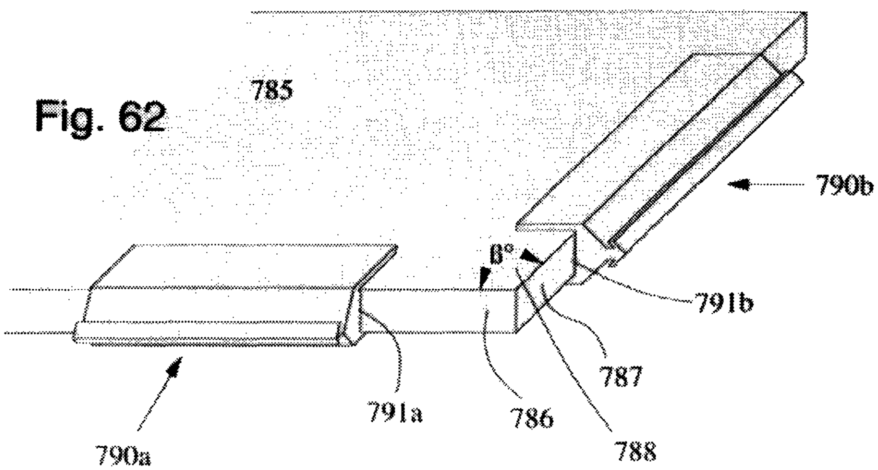


Fig. 62



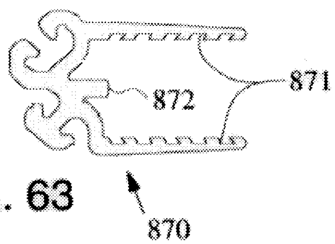
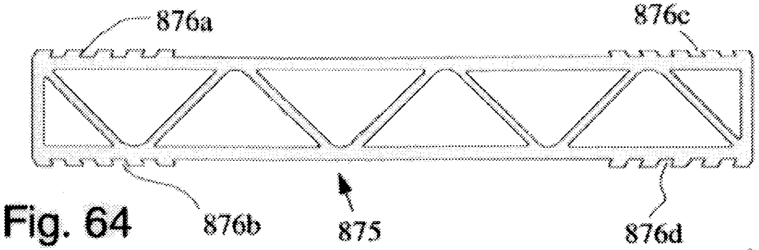


Fig. 63



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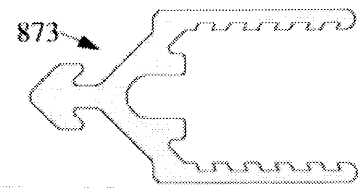

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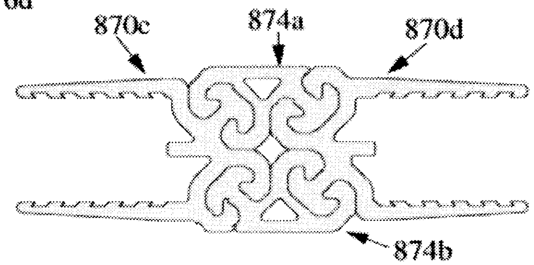

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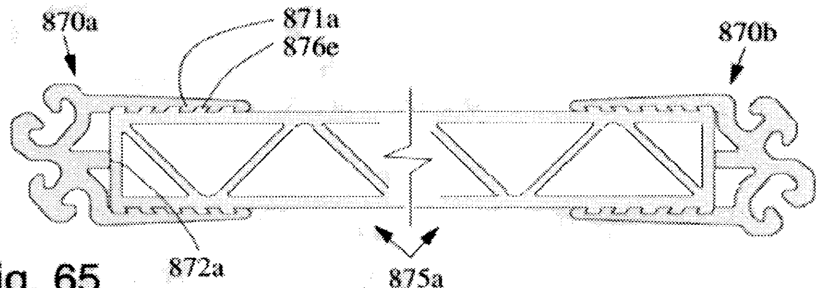

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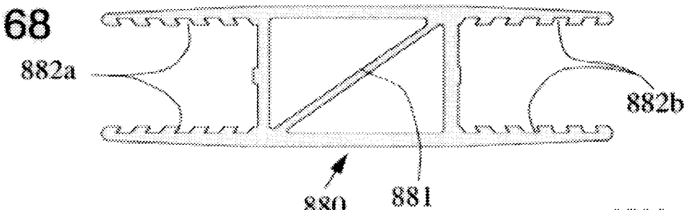

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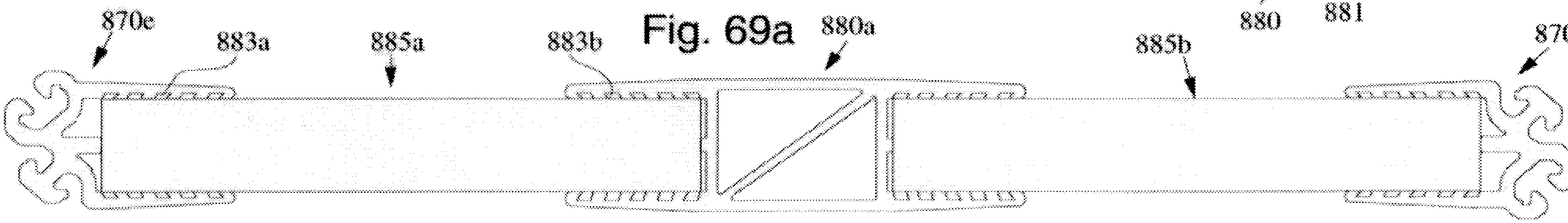


Fig. 69a

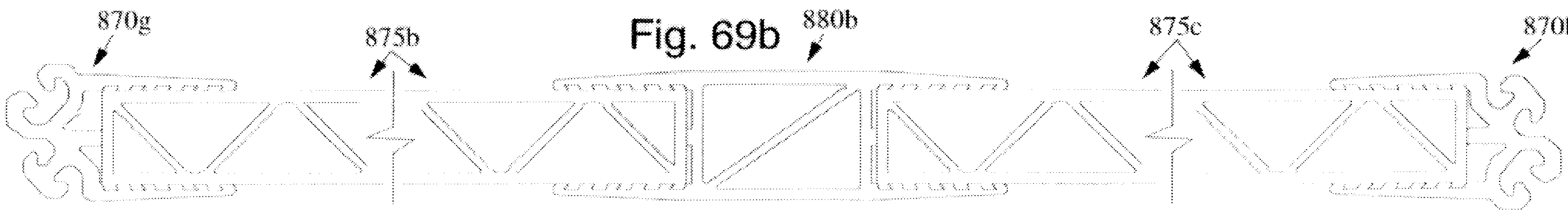
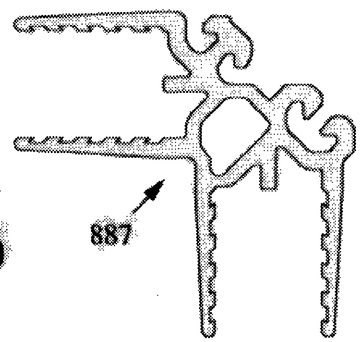


Fig. 69b

290



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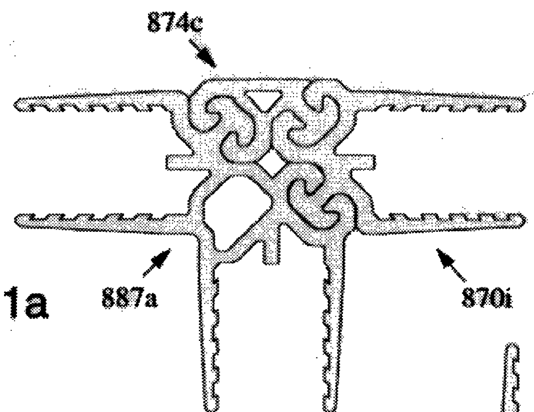

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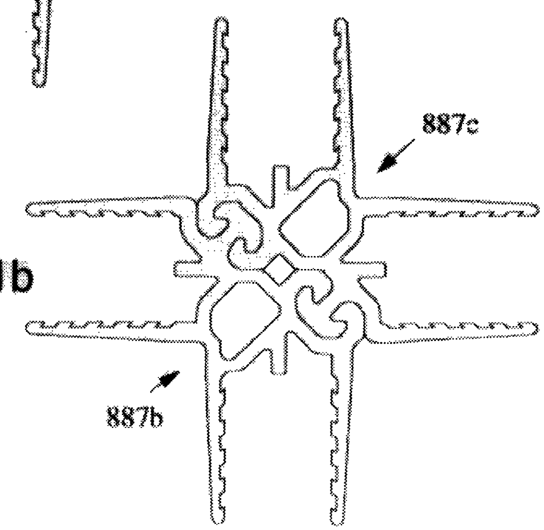
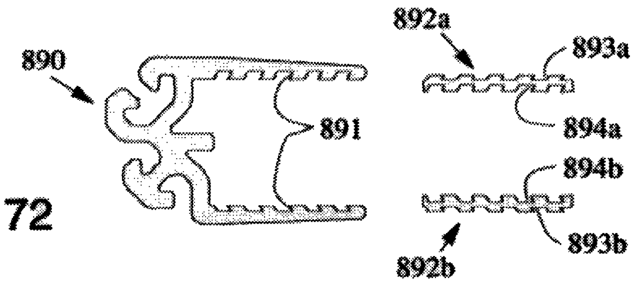


Fig. 71b



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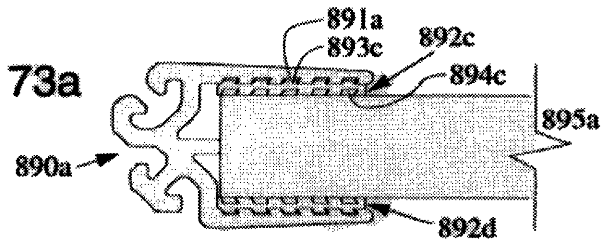


Fig. 73a

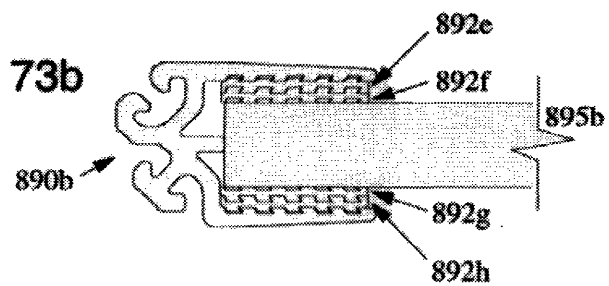


Fig. 73b

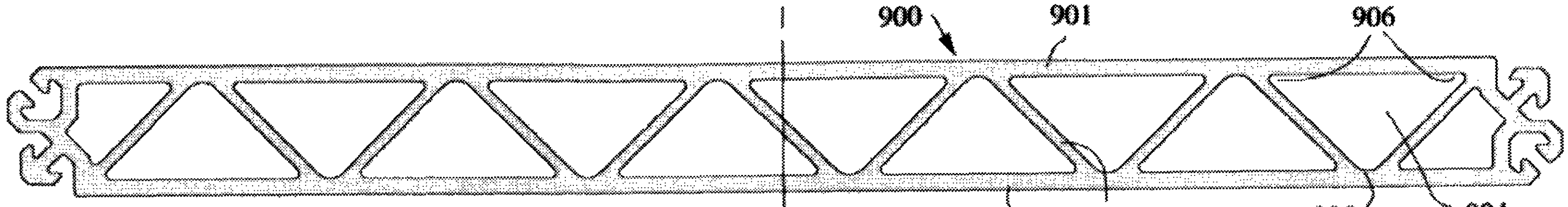


Fig. 74a

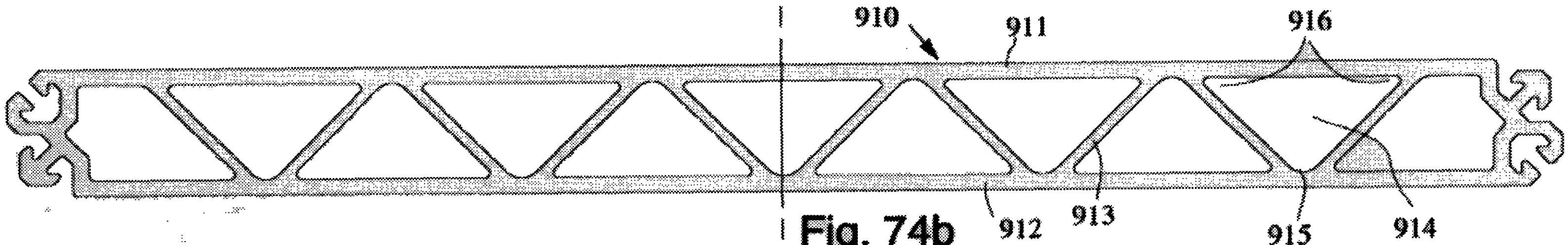


Fig. 74b

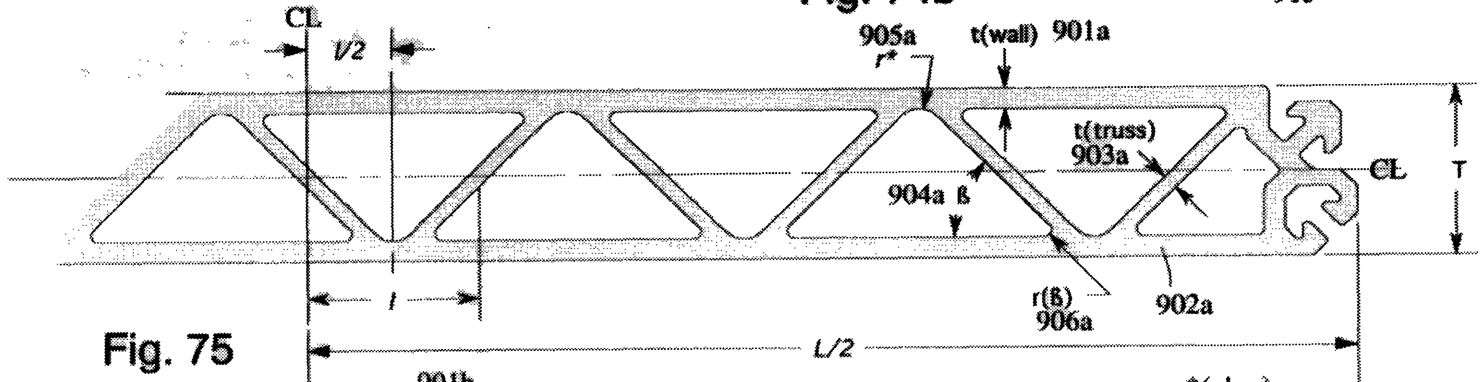
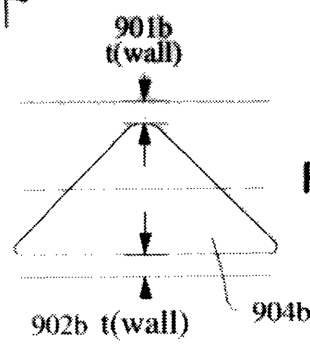


Fig. 75



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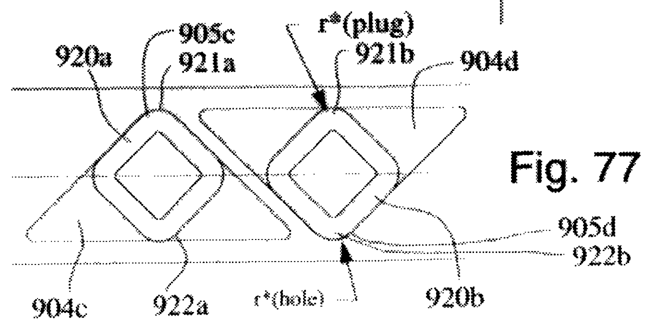

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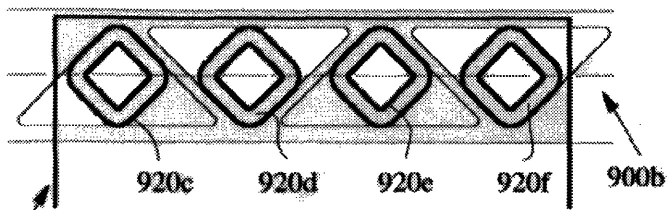

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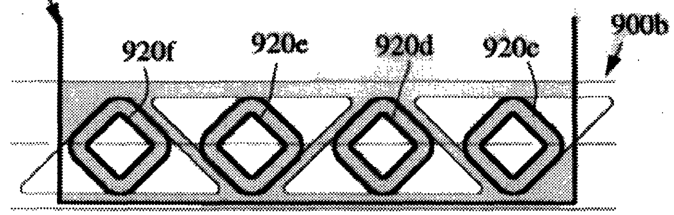


Fig. 78b

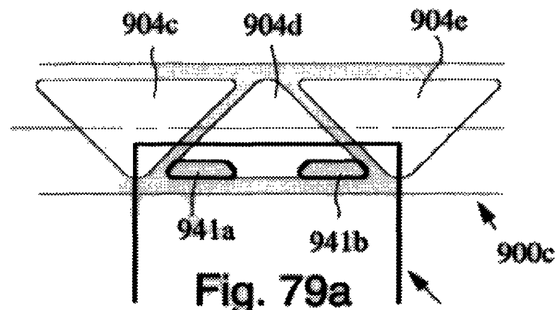


Fig. 79a

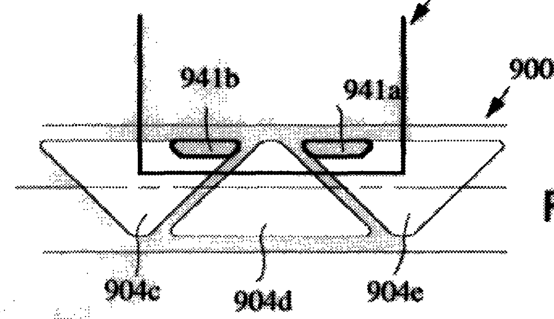


Fig. 79b

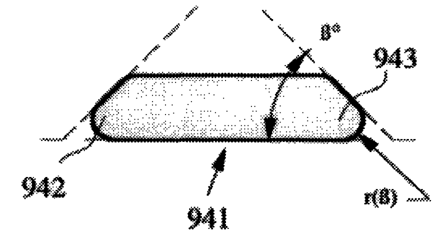


Fig. 80

Fig. 81

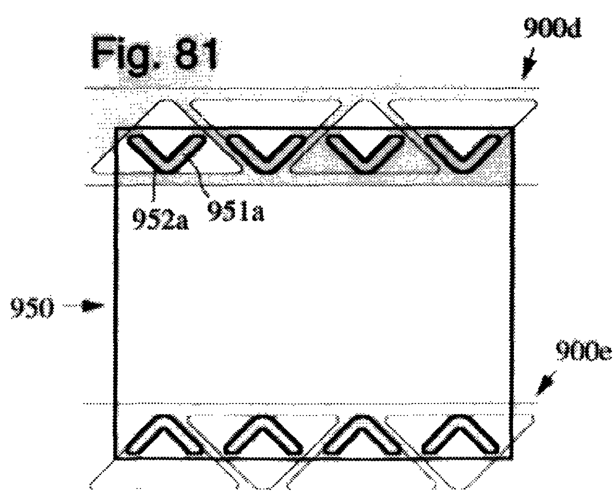
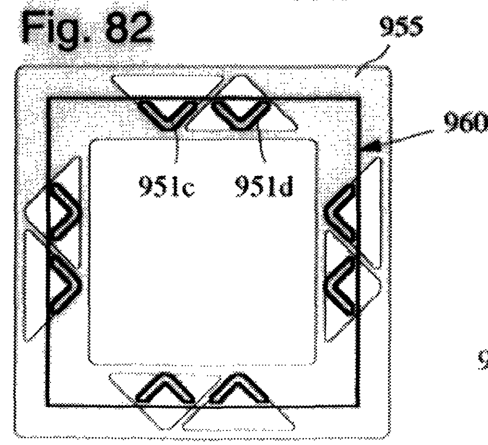


Fig. 82



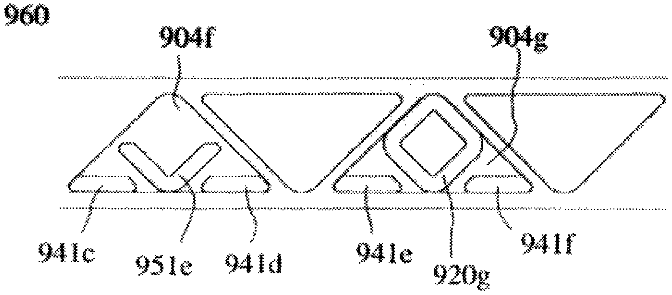


Fig. 83

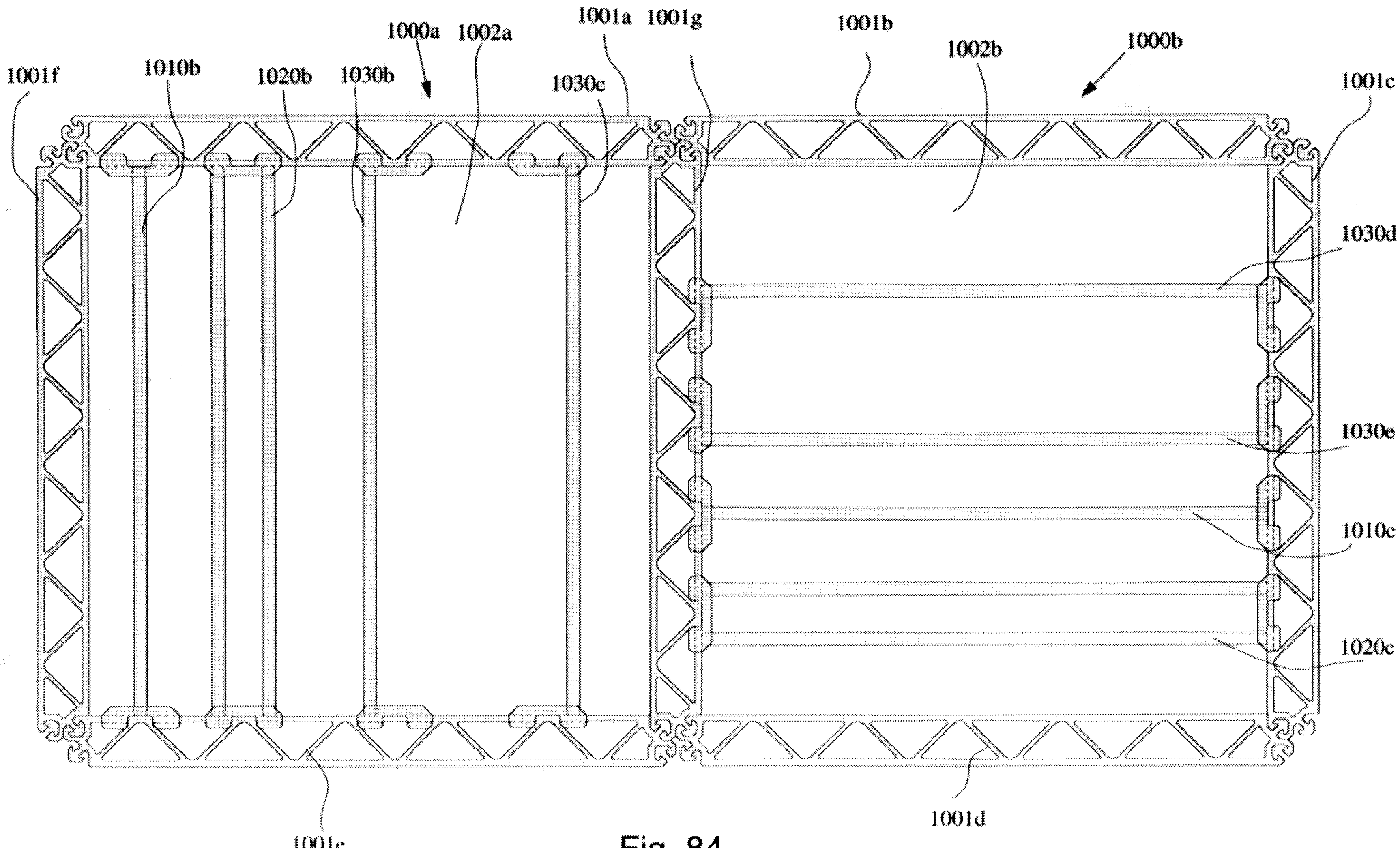

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Fig. 84

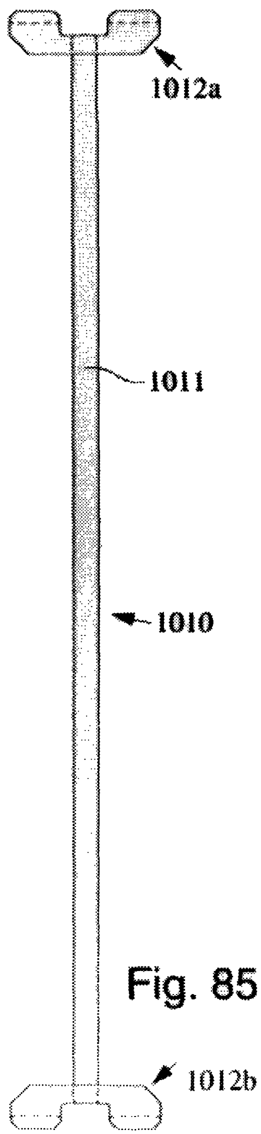


Fig. 85

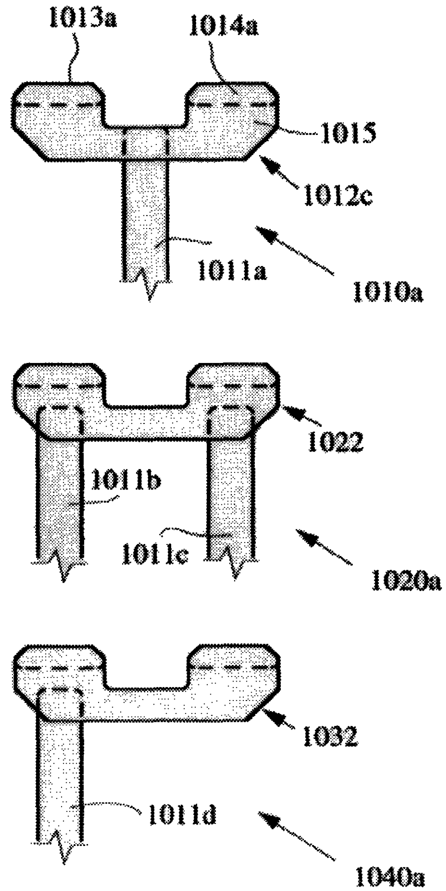


Fig. 86

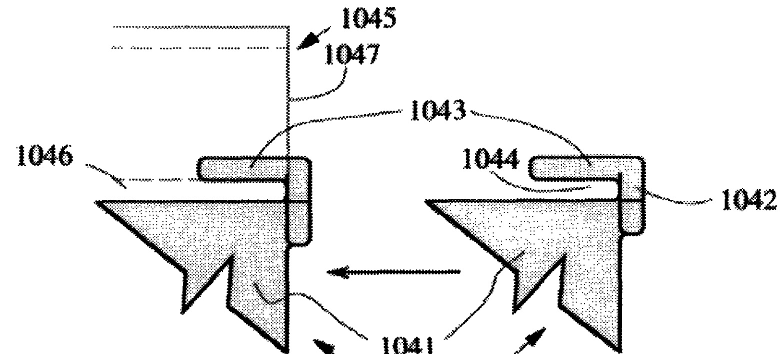


Fig. 87

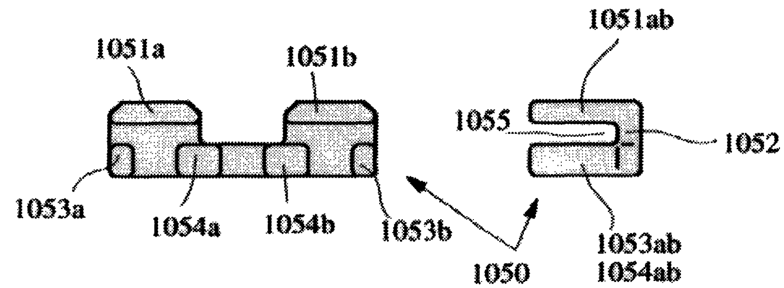
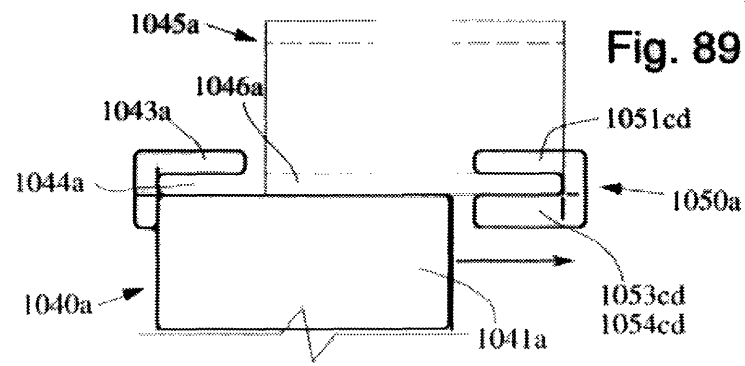


Fig. 88



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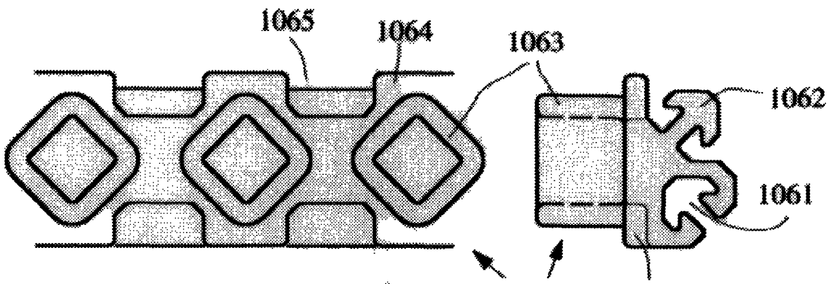
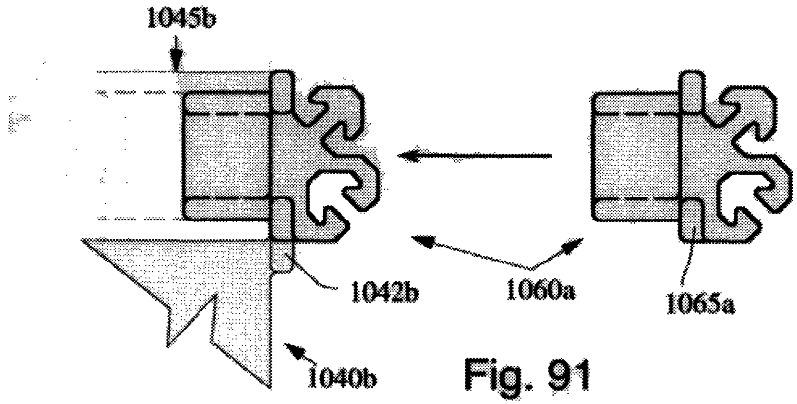


Fig. 90



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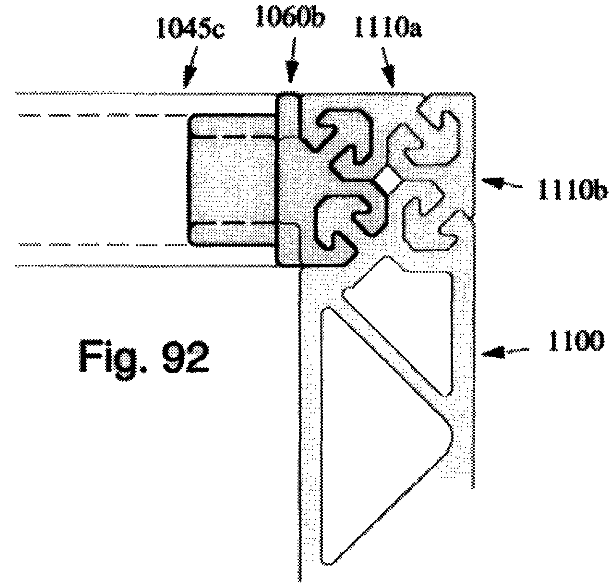


Fig. 92

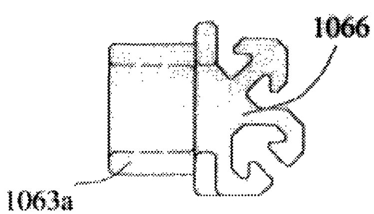


Fig. 93a

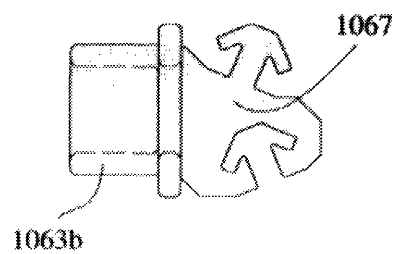


Fig. 93b

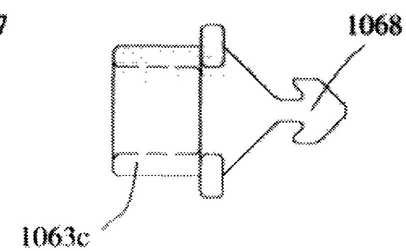


Fig. 93c

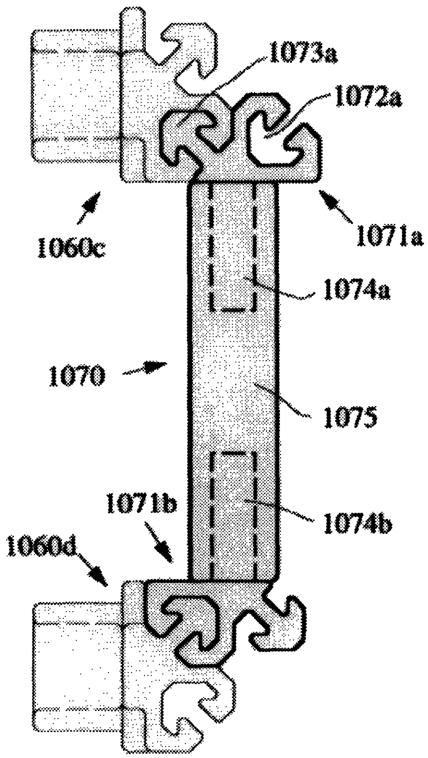


Fig. 94

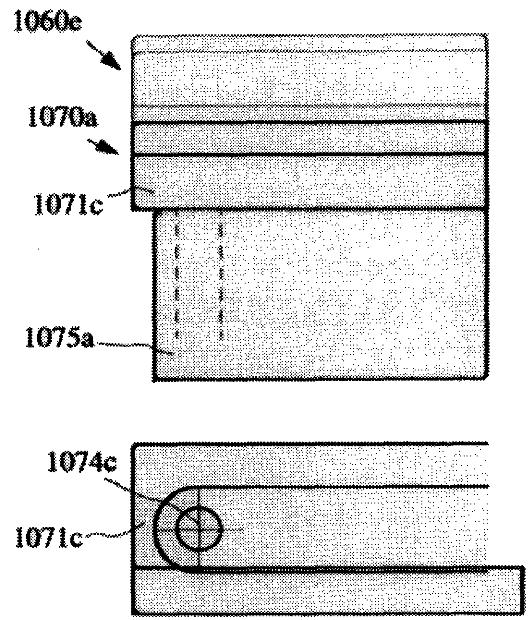
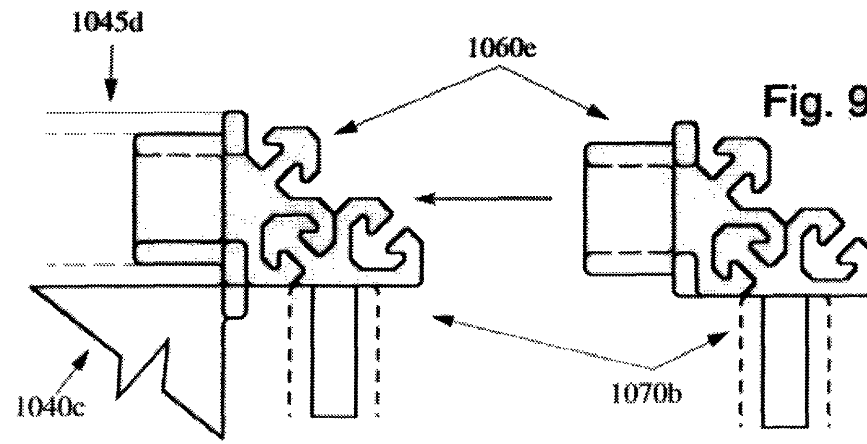


Fig. 95



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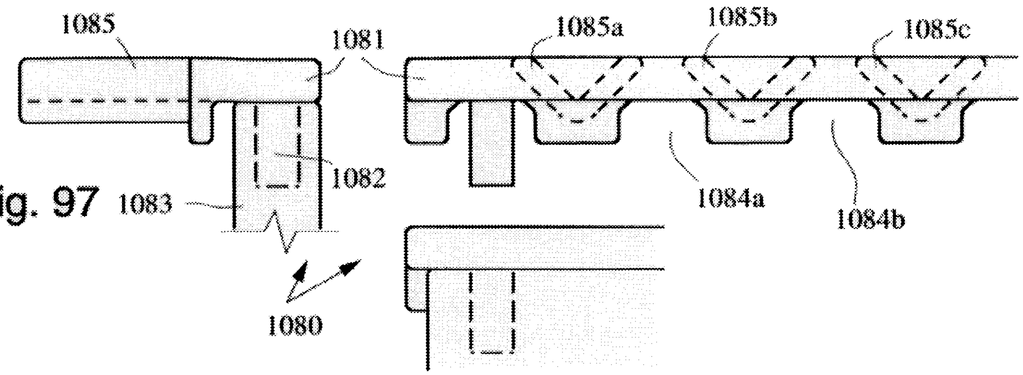

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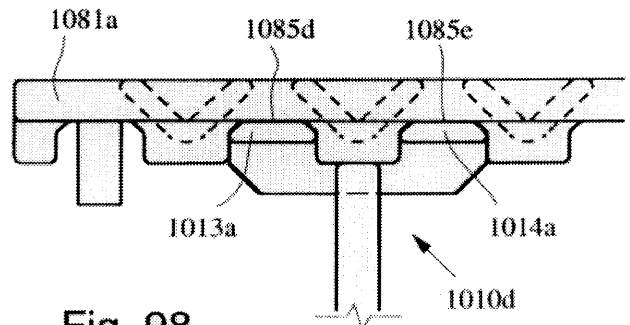

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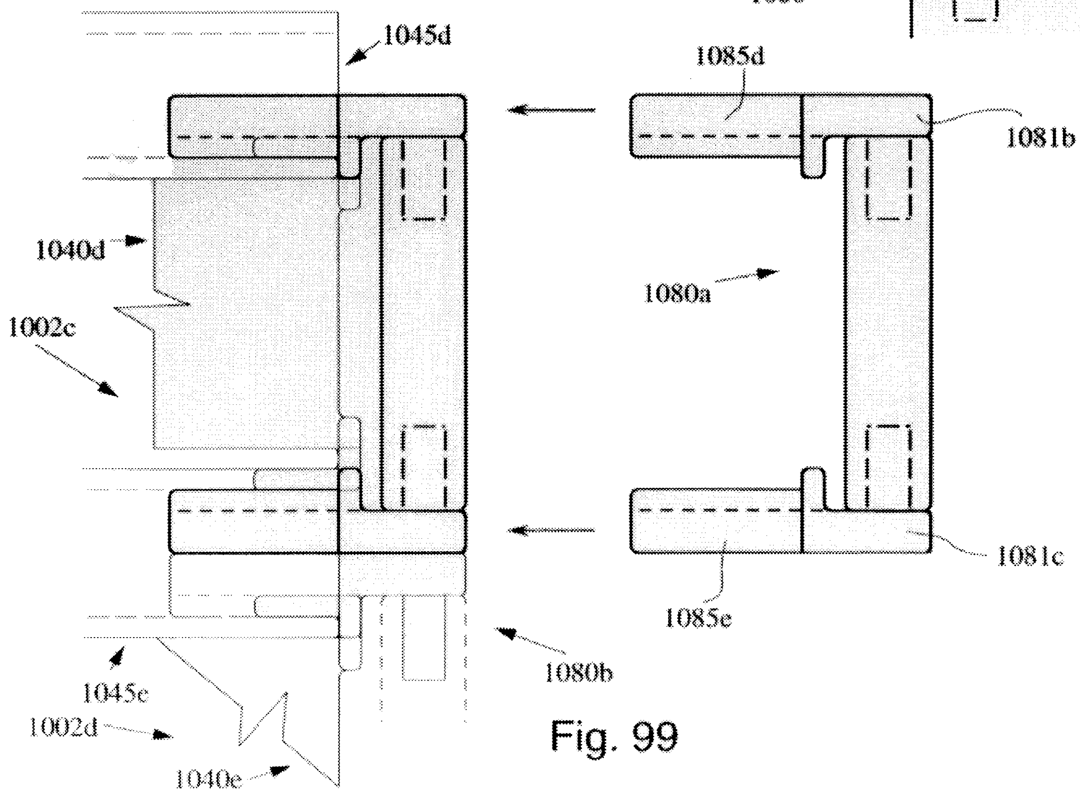

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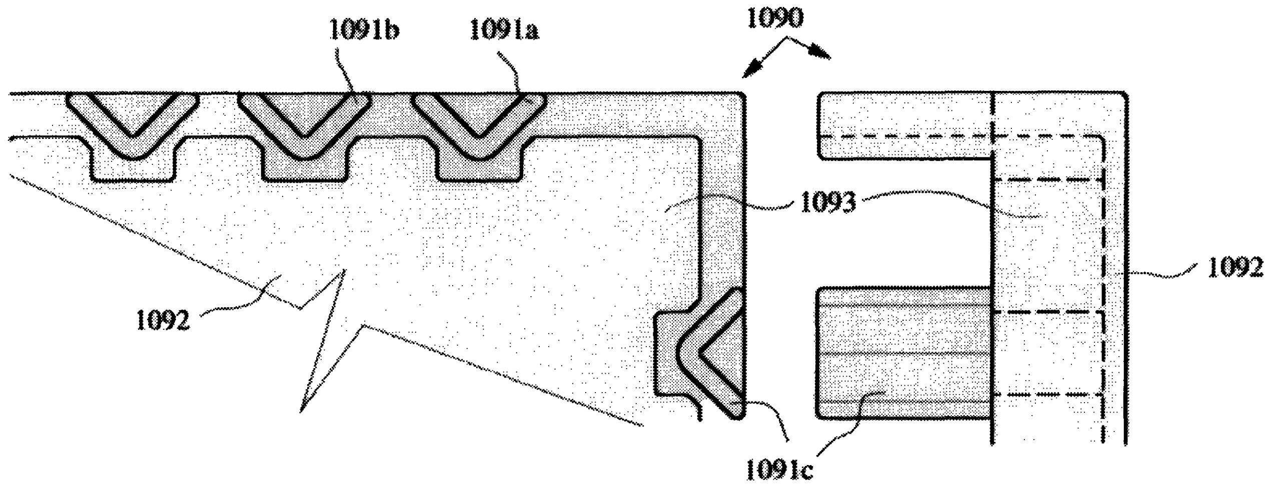


Fig. 100

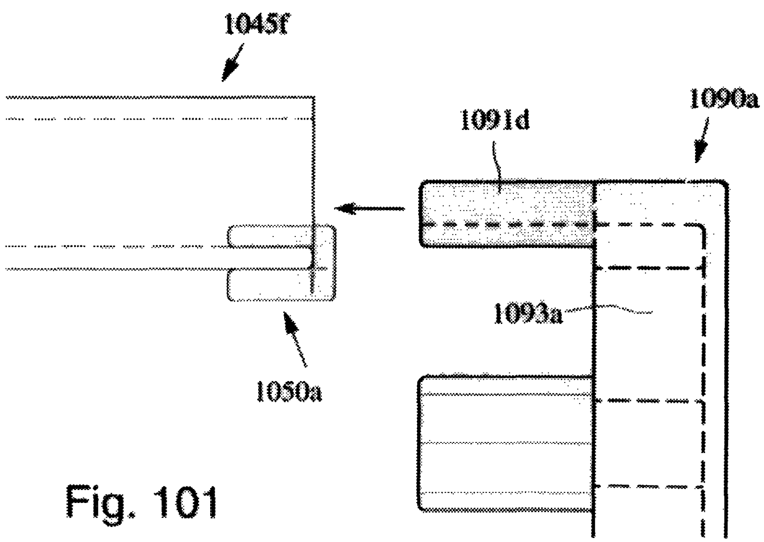
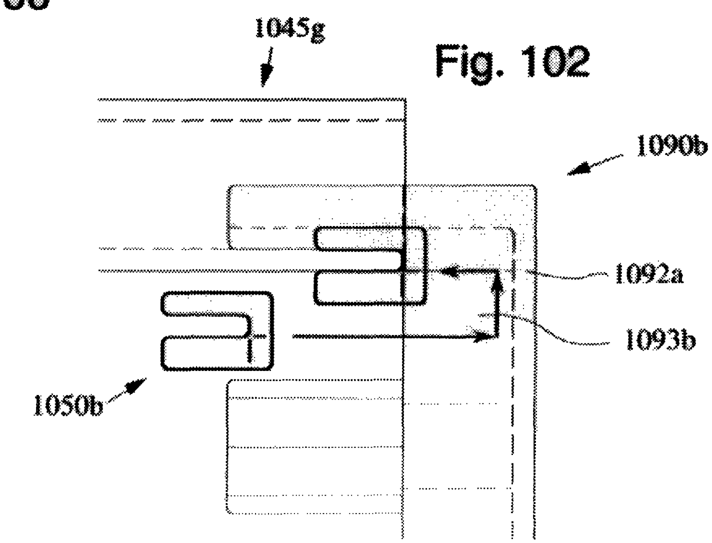


Fig. 101



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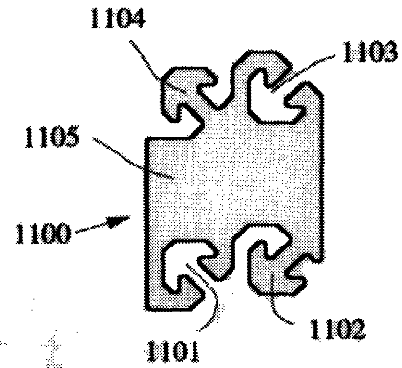
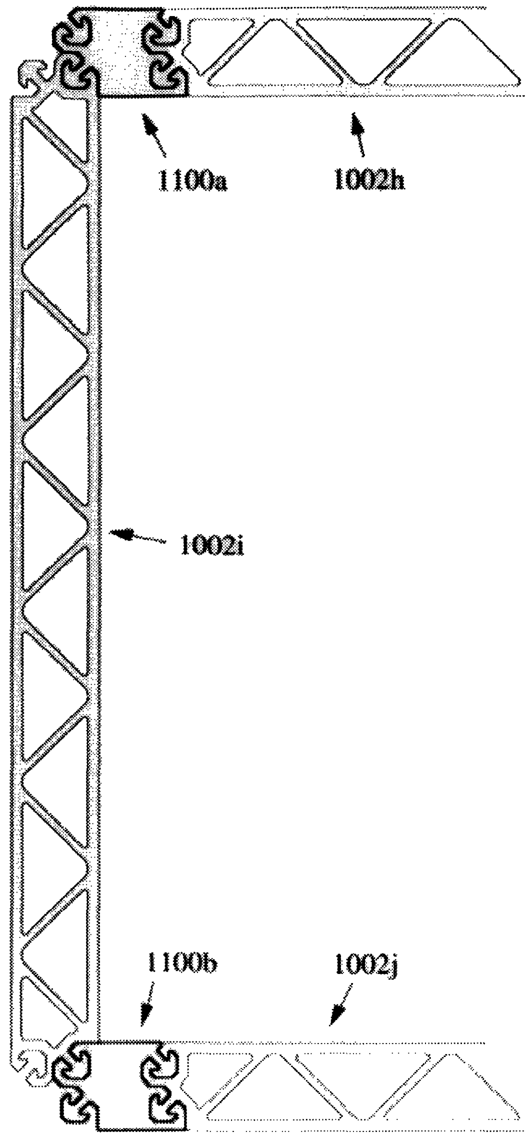


Fig. 103



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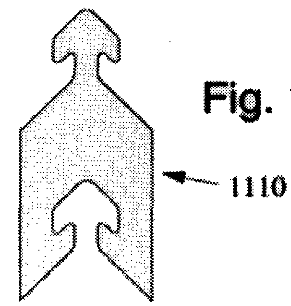


Fig. 105

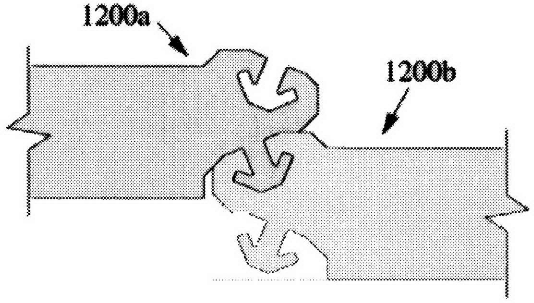
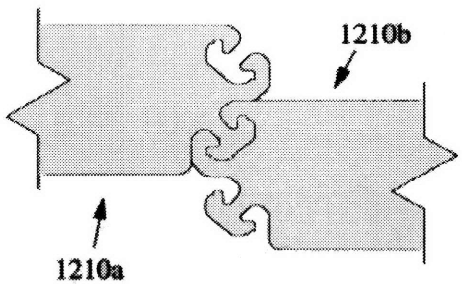


Fig. 106



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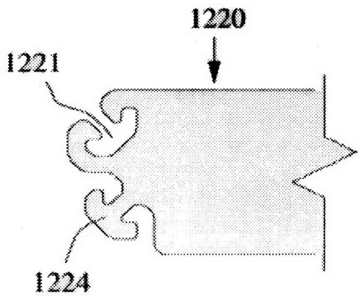

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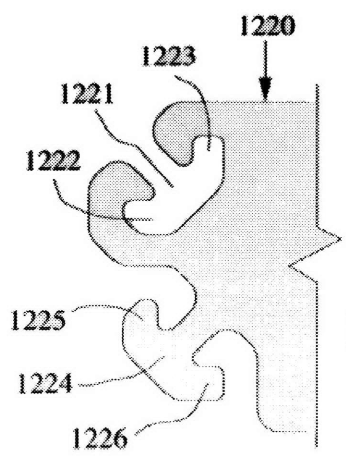

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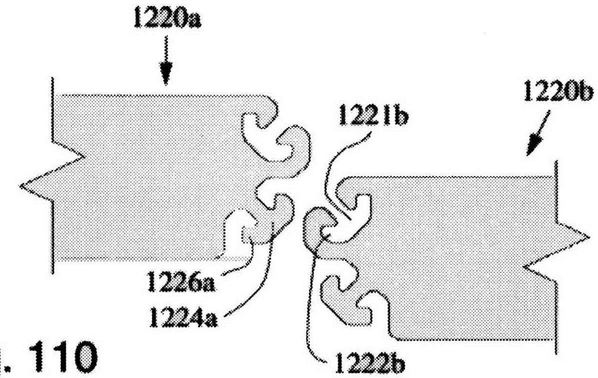

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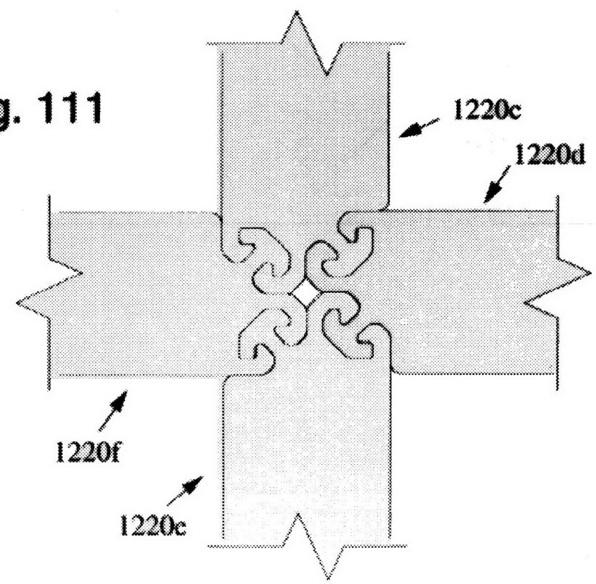


Fig. 111

Fig. 112a

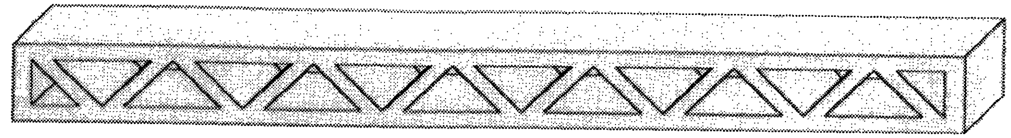


Fig. 112b

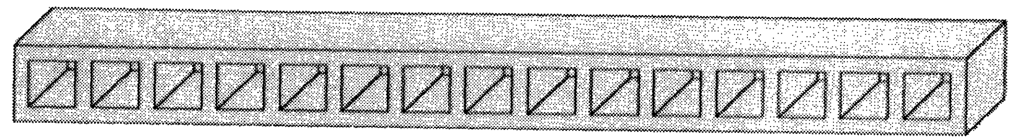
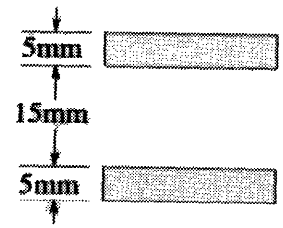


Fig. 113a



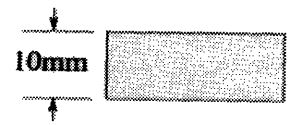


Fig. 113b

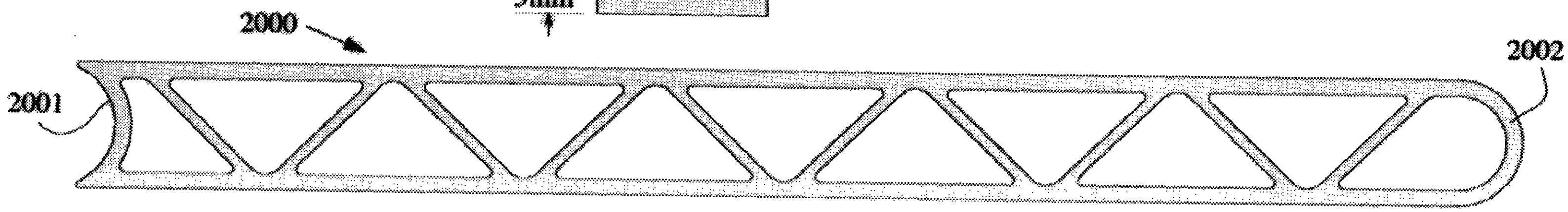


Fig. 114

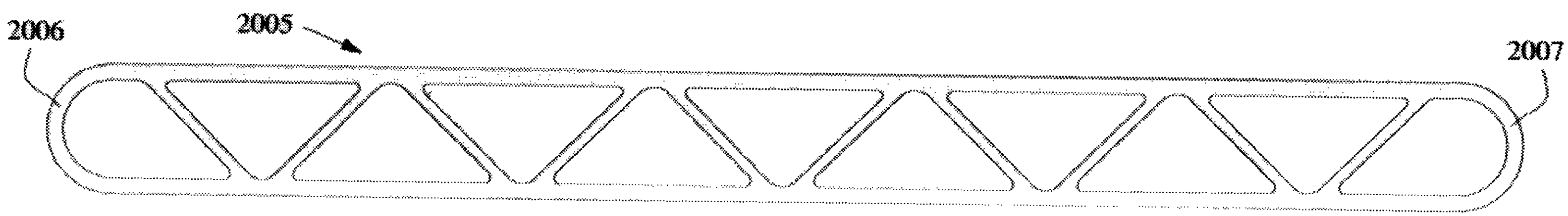


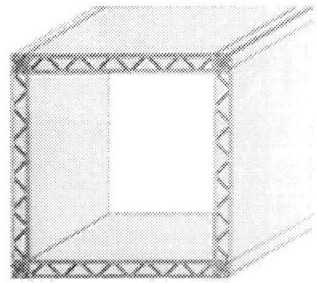
Fig. 115

Appendix C

Product sheets for Cubbeez™ Modular Storage Systems

Cubbeez™ Storage Systems:

Engineered for Your Everyday Storage Needs

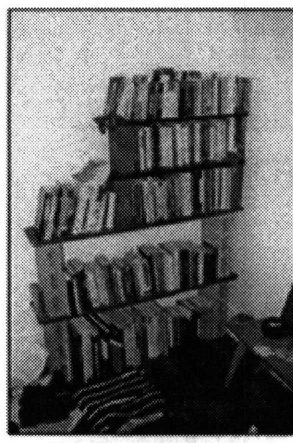


Today's Storage Problems:

All too often makeshift or existing systems fail to provide adequate functionality or performance.

Current "solutions" can be haphazard and unsightly, and often ineffective.

There is a better way...



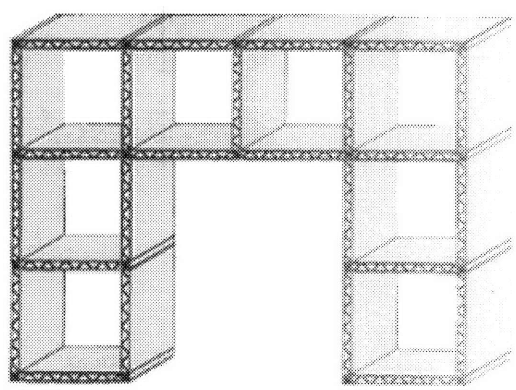
Cinderblock shelves

Buckling crates

The Cubbeez™ Solution!

Novel design-for-manufacture design-for-assembly provide these advantages:

- Expandable
- Lightweight
- Strong & Stable
- Modular
- Easy to Assemble
- Inexpensive
- Uses the AxiBarb™ joint system
- Easy to Accessorize

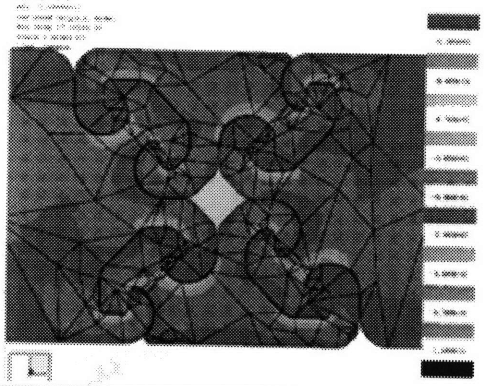


Cubbeez™ Product Sheet page 1 of 2

Featuring the AxiBarb™ Joint --

Engineered for Strength:

Computer-aided design and stress analysis provide proof that the axially-symmetric barb geometry is well-suited for the Cubbeez™ Storage System. Modularity and simple assembly are made possible by the unique AxiBarb™ joint configuration.



- Interlocking barbs resist tension & bending loads
- No joint center-piece
- Distributes forces throughout system
- Minimum part count
- Strengthened by elastic averaging

Superior to Other Joint Systems:

Other joint designs, such as the common dovetail, are inherently weaker than the axially-symmetric AxiBarb™ joint. In both tension and bending finite element analyses, the AxiBarb™ joint is far superior to the other joints tested. The Cubbeez™ storage system with the AxiBarb™ joint is structurally sound and stable.

tension tests 50 lbs. load per 1 inch depth	dovetail	barb	axi-dovetail	AxiBarb
max. stress (psi)	2713	1760	4594	1600
max. displacement (in.) (at origin of applied load)	0.0092	0.0071	0.011	.0074

bending tests 20 lbs. load per 1 inch depth	dovetail	barb	axi-dovetail	AxiBarb
max. stress (psi)	6376	6227	5105	3246
max. displacement (in.)	0.083	0.093	0.040	.036

Smart Design for a Practical Product...

Cubbeez™ Storage Systems

For more information, contact:
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Cubbeez™ and AxiBarb™ designs and principles are patent-pending

Cubbeez™ Product Sheet page 2 of 2

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