Attribute Process Methodology: Feasibility Assessment of Digital Fabrication Production Systems for Planar Part Assemblies Using Network Analysis and System Dynamics

By

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Abstract

A Digital Fabrication Production System (DFPS) is a concept describing a set of processes, tools, and resources that will be able to custom produce an artifact according to a design, fast, cheap, and easy, independently of location. A DFPS project is a complex assembly of custom parts that is delivered by a network of fabrication and assembly processes. This network is called the value chain. Evaluating feasibility of a DFPS project has two main problems: first, how to evaluate assemblability of the design; second, how to evaluate performance of the value chain.

This thesis formulates Attribute Process Methodology (APM); a framework that describes assembly and value chain structure as a network of attributes and processes and uses System Dynamics to evaluate its performance.

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CONTENTS

1 PROLOGUE

1.1 Purpose

Purpose of this thesis is to formulate a framework to evaluate the feasibility of a Digital Fabrication Production System in fabricating, delivering, and assembling an artifact according to a design in terms of risk, time, and difficulty. This framework is intended to support existing CAD design tools and methods, not to replace them. Simply stated, having on one hand a design of an assembly of custom parts, and on the other hand a set of production means, this thesis deals with the question: how difficult is this design to bring to life?

Feasibility assessment of a digital fabrication[1] project is hard if ever reasonable. This is because of the high level of complexity and uncertainty that a CAD/CAM project typically involves. Therefore, feasibility assessment is a strong barrier for the development of CAD/CAM projects.

This thesis approaches feasibility of a CAD/CAM project from two directions: first, from the assemblability of the design; second, from the performance of the value chain.

1.2 Scope

This thesis deals with planar part assemblies, in architecture. However, the theory that this thesis aims to develop can be applied in other kinds of assemblies as well. This thesis assumes the existence of first, a design concept for a planar part assembly and second, information about the production system that will fabricate, distribute and assemble this design. Therefore, in a typical design development process the approach that this

[1] **In this thesis the terms *Digital Fabrication* and *CAD/CAM* will be used with the same meaning.**

thesis proposes should fit between conceptual level and production of detailed drawings.

This thesis explored and brought together material from the fields of Systems Engineering, System Dynamics, Mechanical Assemblies, Product Development, and Digital Fabrication to address the problem of feasibility. It intends to initiate a new field of research in architecture studies rather than close an existing one.

1.3 *Motivation*

This thesis started as a research on defining and solving problems that I faced in digital fabrication projects in MIT during the academic year 2006-2007 (fig. 1-1). During these projects I discovered that as designers we have no formal methods to understand, evaluate, and control production of CAD/CAM projects. At the same time these problems are mainly addressed in the field of product development, industrial management, and manufacturing. My research started as an exploration in these fields in the search of new tools to deal with the complexity of CAD/CAM problems. Gradually it came to my mind the idea that instead of regarding these designs as objects a more useful approach is to regard them as threads of production processes: by unraveling these threads of processes from the final assembly of the artifact up to the primal material resources we map the *value chain* of the artifact. Studying the value chain might reveal useful information about the feasibility of a project.

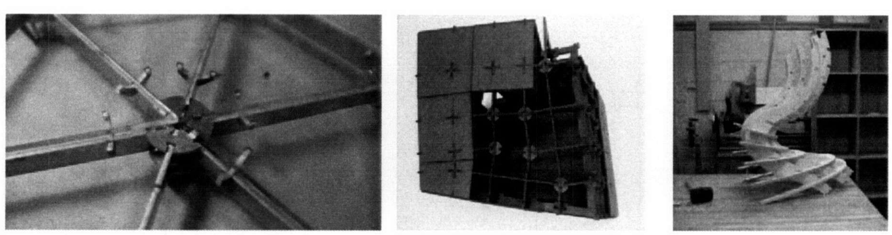


Fig. 1-1: Assemblies of various materials; aluminum, masonite, plywood

1.4 Structure of the Thesis

This thesis is organized in three parts:

- Part I presents the area and the research problem. Part I contains chapters 2, 3, and 4. Chapter 2 introduces the area and the problem of the research. Chapter 3 introduces the concept of the value chain as a way to diagnose the production network of an artifact. Chapter 4 presents the thesis question and my hypothesis, a proposal for addressing this question.

- Part II presents my theory, and my arguments. Part II contains chapters 5, 6, 7, and 8. Chapter 5 introduces basic concepts from Systems Theory that will be used in the next chapters. Chapter 6 deals with the artifact and with two methods to describe it: the assembly description and the CAD description. Chapter 7 deals with the value adding process, the fundamental building block of a value chain. Chapter 8 integrates chapters 6 and 7 to present the concept of the value chain.

- Part III presents the results, my conclusion, and thoughts for future research. Part III contains chapters 9, and 10. Chapter 9 presents my results and finally chapter 10 closes this thesis with my conclusion and future research suggestions.

PART I - VISION

Structure of part I

Part I is organized into four chapters: chapters 2, 3, and 4.

- Chapter 2 introduces the area, the mission, and the problems of a Digital Fabrication Production System (DFPS). A DFPS is a decentralized network of processes that ideally should be able to build anything, anywhere that matches the constraints of the system. Chapter 2 concludes that the problem is the lack of proper description tools: we need tools to describe processes rather than solely states.

- Chapter 3 introduces the concept of the value chain as a way to map the production network of an artifact. The value chain describes the threads of all the processes and resources that are required to bring the artifact to life; it begins from the primal resources and it ends in the final assembly.

- Chapter 4 presents the thesis question and my hypothesis, a proposal for addressing this question. *Can an artifact A be delivered by a value chain B, according to a design description C? If so, then how feasible is it?* Chapter 4 first decomposes the thesis question into two components: Assemblability of the design; and feasibility of the value chain. Assemblability deals with the structure of a system while feasibility deals with the dynamics of a system. This thesis speculates an approach that combines a structural description of the artifact into a dynamics description of the value chain.

2 INTRODUCTION

2.1 *Overview of chapter 2*

Chapter 2 introduces the area, the mission, and the problems of a Digital Fabrication Production System (DFPS). A DFPS is a decentralized network of processes that ideally should be able to build anything, anywhere that matches the constraints of the system. Chapter 1 concludes that the problem is the lack of proper description tools: we need tools to describe processes rather than solely states.

2.2 *The embodied difficulty of a design*

Every design embeds a certain degree of difficulty of production. This degree depends partly on the difficulty of the fabrication methods of its building components, partly on the difficulty of their distribution from fabrication to assembly, and partly on the difficulty of their assembly. For example, a design of highly customized parts with complex interfaces that will be fabricated and assembled in different locations by different teams, has a higher degree of difficulty from a design of standard parts with simple interfaces that will be fabricated and assembled at the same location by the same teams. This is because first, the parts need specialized manufacturing and second, the assembly will take more time and require more skilled labor; moreover it has a higher risk of failure. Therefore, estimating the difficulty of production of designs is significant information for improving design.

2.3 *A Digital Fabrication Production System (DFPS) for Mass Customization*

Current studies in digital fabrication focus on automating design and fabrication of assemblies of planar interlocking parts that are manufactured at custom shapes using 3-axis CNC technology (Sass, Michaud, and

Cardoso, 2007). Ultimate goal of these studies is to define a *Digital Fabrication Production System* that uses CAD/CAM technology to mass-customize assemblies of planar parts. Currently, these studies are trying to define the solution space of such a system as a function of design intelligence, manufacturability, and assemblability: On one hand, these studies explore high-end computational generative design methods to decompose a solid model into constructible parts that will be instantly fabricated and assembled with little skill. On the other hand, these same studies study physical mockups of the designs by hand assembly to evaluate assemblability. Why so much technology is invested on design generation while empiricism is invested on analysis and evaluation? These approaches simply verify the complexity in evaluating feasibility of a digital fabrication project.

2.3.1 *Definition of a DFPS*

A Digital Fabrication Production System is a decentralized network of fabrication, distribution and assembly processes that use tools and resources to produce an artifact according to a given design at a specified location, time, and cost. The set of possible designs that can be produced is limited by tool, resource, and distribution constraints. A key concept of a DFPS is the network based framework: the success or failure of a DFPS depends greatly on its ability to work collaboratively as a network of production processes. In this respect the distance and location of the various production processes from the construction site becomes a parameter of the design.

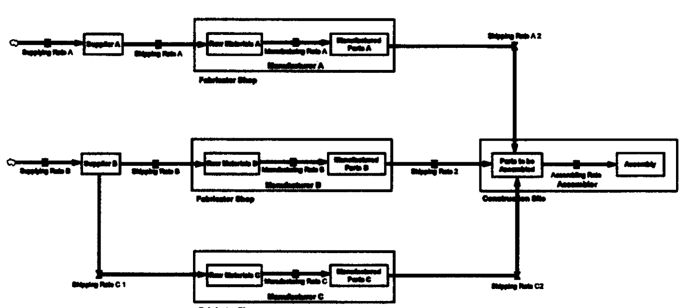


Fig. 2-1: A stock & flow structure of a System Dynamics model of a supply chain

2.3.2 *Artifact of a DFPS*

The artifact of a DFPS is typically an assembly of a combination of custom and standardized parts. Generally speaking, the greater the number of the standard parts, the less flexible the design is; on the other hand, the greater the number of custom parts, the more expensive and time consuming the production is. CNC technology has enabled fast production of customized parts. However, the production rates and cost of CNC-based mass customization methods still cannot compare to the ones in mass production. Therefore, much of the current research focuses on determining the line between standardized and custom parts in the artifact. For example, by embedding more intelligence in the design, all the geometric complexity can be concentrated on the customized parts leaving the joints or fasteners to be standardized. This strategy would greatly improve design and reduce production cost and time. Another direction of current research, aims to design strategies of self locating parts, to reduce assembly time and the number of required fasteners similarly to a jigsaw puzzle. This however perplexes assembly process because the solutions for properly constraining parts becomes complex. This thesis steps on these directions and focuses on assemblies of planar parts.

2.3.3 *Organization of a DFPS*

The workflow concept of a DFPS is the following: begin design process with a custom geometric form, preferably in a CAD file format; decompose it into constructible parts; send the part files for fabrication to various locations; transport all parts at the construction site at the right time; finally, assemble the final artifact. Conceptually it means that based on a network of production and distribution processes we could build anything we want, at anyplace, at controllable cost and quality.

Fig. 2-2: Workflow concept of a DFPS

The number and location of the fabrication and assembly stations is a parameter of the system. Ideally, all fabrication and assembly should take place in the construction site to reduce transportation time and cost. This however is still not possible because there is not always enough space in the construction site to set up the fabrication stations; therefore the success of the system depends not only on the design solution but also on the means and methods that will execute the design.

Every project is organized into design, fabrication, and assembly, the coordination of which determines the performance of the production. Since assembly is still manually performed, the idea of a DFPS is to focus technology and knowledge on design to facilitate manufacturing and assembly.

2.3.4 *The Vision*

The aspirations of a DFPS are the following: custom shapes, controllable lead time, controllable quality, controllable cost, easiness of fabrication, and easiness of assembly. Simply stated this means to build any form, anywhere, accurately, cheap, fast, and easy.

2.3.5 *The Reality*

Unfortunately, the reality with CAD/CAM projects is rather disappointing: They take more time than what was planned, they get more expensive than what was expected, they involve great risk and uncertainty, and finally they are too complex to plan, understand, and manage. Moreover, most of these problems are discovered during production when it is already late for correction. All these observations are symptoms of two main problems: first, assembly incompatibilities. Second, bad supply chain behavior.

However, there is currently no systematic approach to evaluate difficulty of production of CAD/CAM projects. Most of current risk assessment methods are based on experience gathered from previous similar cases. But it is the premise of mass customization that projects can be radically different. Assembly incompatibilities are currently addressed by building physical mockups. But physical mockups cause a significant loss in both time and cost. All these problems suggest that an introduction of a DFPS for mass customization in architecture needs first a firm theory of assembly and management control.

2.3.6 Problem Definition

If problems are faced in production then the problem should be traced in planning. The inconsistencies between design and reality suggest that designers still lack the necessary tools to deal with the complexity of digital fabrication projects and evaluate design feasibility before production starts. This thesis deals with the following problem:

How can we define a formal method to evaluate the difficulty of production of an artifact if we know the artifact's design and the production system's structure?

This thesis will approach this problem from two directions: first, assemblability assessment of design; second, feasibility assessment of production flow.

3 BACKGROUND

3.1 *Overview of chapter 3*

Chapter 3 introduces the concept of the value chain as a way to map the production network of an artifact. The value chain describes the threads of all the processes and resources that are required to bring the artifact to life; it begins from the primal resources and it ends in the final assembly.

3.2 *Design & production*

The inconsistencies between design and production of digital fabrication projects bring the question of the role of design and its relation to the artifact. This hesitation seems to stem from the dual nature of design both as a representation of the form and as a description of its production process. The role of design as an implicit representation of form or as an explicit description of production process depended always on the structure of the production system. However, today it seems that while production system has changed, the design strategy has remained the same.

3.3 *The Role of Design*

According to Herbert Simon sciences are classified into natural and artificial (Simon, 1996). Natural sciences describe the natural world. Sciences of the artificial describe artifacts of human intervention in the natural world; artifacts are conceived by design. Architecture is a science of the artificial; it is the science that describes edifices that will be built by human intervention in the natural world. The word *intervention* includes the technology that the human mind will use to create the artifact. The word *natural* emphasizes that the purpose of the design is to describe something that will be produced in the physical world. Therefore, in architecture there is a close relationship between design description and production means. Design is the means to conceive and describe the artifact that will come to the natural world.

Therefore, there is close relationship between design description and production means; design constraints should depend on (a) physical and (b) production constraints.

3.3.1 *What Matters in Design?*

The question then is: what matters in design? Is it the description of the artifact or the description of the process to make the artifact? But before asking this we should perhaps first query on the nature of the artifact: when does the artifact start to exist, is it during design or during production? To answer that we have to carefully trace the processes that bring the artifact into life; we will call this the *value chain.* By observing how the structure of the value chain has changed in time we shall be able to draw conclusions on the current role of design.

3.4 *The value chain*

The value chain, a term coined by Michael Porter (Porter, 1998), but explored before by Taiichi Ohno (Ohno, 1988), and later by James Womack and Daniel Jones (Womack, and Jones, 1996), describes the thread of all the processes and resources that are necessary to bring the artifact to life, from design to production. It starts from conceptualization, procurement of raw amorphous matter, transformation of matter into building components, and finally assembly of the components to form the actual artifact. The value chain should not be perceived as a linear structure; instead it is a network often with significant complexity. On every step of the chain, processes add value to the artifact and gradually turn the amorphous disordered matter into ordered form. We call these processes, *value adding processes*

3.4.1 *The Value Adding Process*

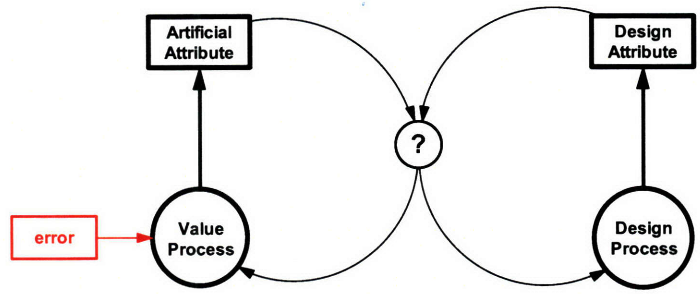


Fig. 3-1: Value adding processes and design processes.

Value adding processes are the processes which embed *design information* into the matter[2]. There are two main types of value adding processes: *transformation* processes and *aggregation* processes (fig. 3-2). Transformation processes change the form or the state of materials (fabrication) to make parts. Aggregation processes put parts together to form larger complexes (assembly). A value adding process has an error factor that introduces noise in the outcome of the process. Chains of value adding processes propagate errors. There are two correction options: redo the process or redo the design (fig. 3-1).

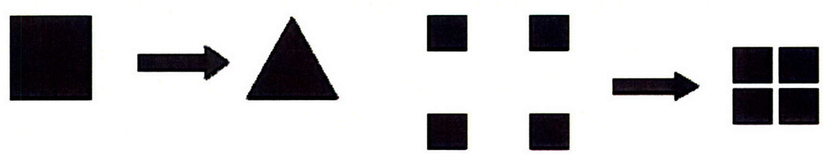


Fig. 3-2: Transformation and aggregation processes.

The processed artifact embodies and conveys design information from fabrication processes to assembling processes formulating a communication stream between designers, fabricators, and assemblers. For example, a fabricator that follows designer's instructions to form two interlocking parts with a peg and a hole explicitly conveys the assembling instruction to the assembler through the form of these two parts.

[2] According to Simon, the amount of design information that is embedded in an artifact relates to its entropy; entropy measures the amount of uncertainty of information. See Simon, *The Sciences of the Artificial, 189.*

3.4.2 *Structure of the value chain*

The structure of the value chain greatly affects the design of the artifact because it determines the type and amount of design information that can be embodied and conveyed through the value adding processes. For example the physical constraints of the transportation network, the suppliers' resources, the manufacturing tools, and the assemblers' capacity determine the size and shape of the manufactured components that will flow through the value chain.

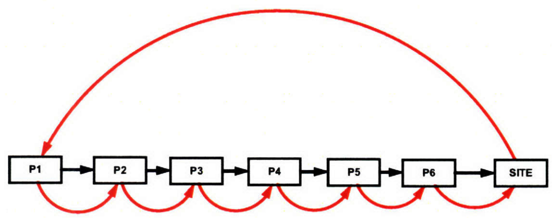


Fig. 3-3: The longer the value chain the more time it takes to respond to an error.

Therefore, the position and distribution of the value adding processes in the value chain is a strategic decision. The more concentrated and the closer the value adding processes are to the construction site, the less the noise and constraints of the chain to the artifact are. On the other hand, the more distant the value adding processes are from the construction site, the more vulnerable the artifact is on the noise and constraints of the structure of the network (Fig. 3-3). Compare for example the probability of failure of the production of an artifact whose parts are fabricated by a number of different fabricators located at remote places from the construction site, to the probability of failure of the production of an artifact whose parts are fabricated by only one fabricator located inside the construction site. Clearly the first case is exposed to higher risk of failure. It turns out that the position and relationship of the value adding processes determines the role of design either as explicit or implicit instruction in a value chain. If design is explicit, its purpose is to direct; if design is implicit, its purpose is to indicate. In the previous example it is clear that in the first case the designer needs to explicitly define all design instructions before the production starts. In the second case however, the designer can implicitly define or even modify design instructions during production since all value adding processes are in the construction site. The position and relationship between fabrication and assembly processes in the value chain varied throughout history. A careful observation of their relation reveals important conclusions about the role of the design in each case.

3.4.3 The traditional and the digital value chain

3.4.3.1 The Traditional value chain

In the traditional value chain fabrication and assembly took place at the final step of the chain (fig. 3-4). Both transformation of raw materials to building components and assembly of the building components to formulate the artifact are handled by the *builder* in the construction site. The designer would know *what,* but the builder would know *how*. The traditional value chain was experienced based: a great amount of decisions was taken on site. Therefore, design in the traditional value chain was an implicit description of form.

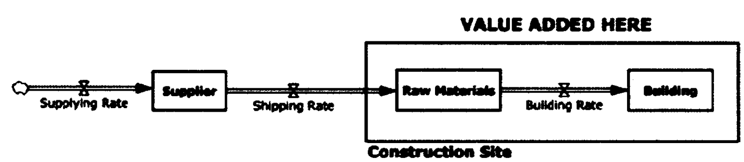


Fig. 3-4: The traditional value chain

3.4.3.2 The digital value chain

In the digital value chain fabrication and assembly take place at different steps in the chain (fig. 3-5). Now, the transformation of raw, amorphous materials into building components takes place in the middle of the chain by the *manufacturer* but the assembly of the components takes place at the end of the chain, by the *assembler*. The designer needs to know both *what* and *how* and instruct manufacturer and assembler. The digital value chain is knowledge based: all decisions have to be taken before production starts. Therefore, design in the digital value chain is an explicit description of processes. For example, the assembler can not use his experience to assemble a number of pre-manufactured parts because the assembly sequence is already determined by the designer. As a consequence, any mistake during design process is irreversible if manufacturing of parts has taken place.

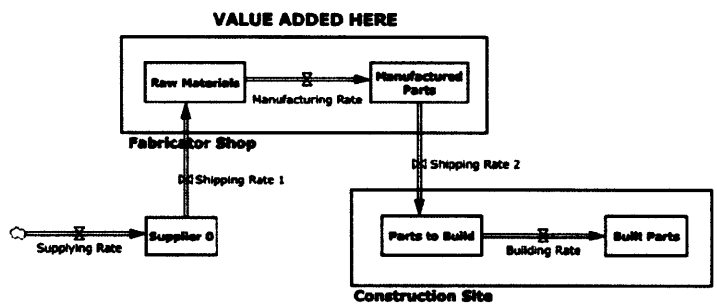


Fig. 3-5: The digital value chain

3.4.4 *Value chain differences between the manufacturing and the building industry*

One of the greatest differences between the manufacturing and the building CAD/CAM industry is that no matter how precise the digitally controlled fabrication processes are in the building industry, the success of their assembly depends on manually controlled processes that setup the foundation. For example any prefabricated parts will be supported on manually excavated foundations. Therefore, in the building industry there is greater risk of error. Another difference is that in the manufacturing industry the assembly processes typically take place before the final delivery to the destination of the value chain. In the building industry assembly processes typically take place after the final delivery to the destination of the value chain, the construction site. These observations bring the following paradox of CAD/CAM construction systems: from one hand we want to draw all of the digitally controlled value adding processes before the construction site. From the other hand most of the manually controlled value adding processes happen in the construction site, after the digitally controlled processes have taken place when it is already too late. When preplanning it is impossible to take into account the problems that may occur.

3.5 *The artifact of the digital value chain: complex assembly*

This thesis defines the digital artifact as the product of the digital value chain. From this definition follows that the digital artifact has a dual aspect: from one hand, as an object it is a complex assembly of customized parts; from the other hand, as a process it is the result of a complex system of collaborating value adding processes.

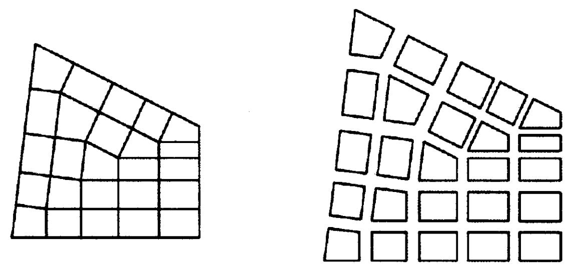


Fig. 3-6: The artifact of a DFPS

3.6 *Previous Work*

Assemblability in Architecture has been addressed by CAD modeling and physical mockups with little understanding of the problem. Assembly structure and production flow have been studied using Network Analysis and System Dynamics in Product Development, Industrial Management, and Manufacturing. However an integration of how a design might affect production flow of a value chain is still missing in architecture.

3.6.1 *Previous Work in Digital Fabrication*

Previous research in understanding assemblability in architecture has focused on two main directions: CAD modeling (3D, 4D) and Physical Mockups.

3.6.1.1 CAD 3D

CAD 3D modeling has been used for modeling assemblies. However, 3D modeling represents the final state of the assembly, when all parts have been put together, but not the process of putting these parts together (fig. 3-6). Moreover, the order of constraint delivery in CAD models has nothing to do with the actual constraint delivery of the real assembly. As a consequence, by studying a CAD 3D model, the designer cannot tell if a design is assemblable, nor he or she can estimate the difficulty of the assembly.

3.6.1.2 CAD 4D

CAD 4D modeling has been used for clash detection during assembly sequence. However, 4D modeling fails similarly to describe actual constraint delivery between parts. Moreover, the effort to develop a detailed CAD 4D model that simulates assembly sequence is a restraining factor. Finally, CAD 4D simulates or rather animates an existing assembly sequence; however it is not able to define a proper assembly sequence.

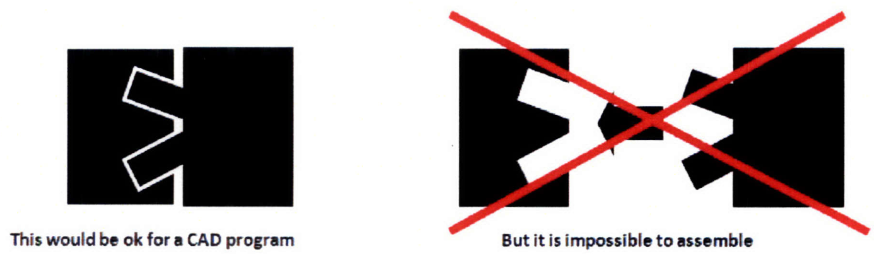


Fig. 3-7: the design on the left is valid for a CAD program but it is impossible to assemble

3.6.1.3 Physical mockups

Physical mockups have been used during design development to test assemblability (Sass, Michaud, and Cardoso, 2007). However, there is a significant loss in time and cost. In this fashion, testing is empirical, understanding the solution to the geometrical problem is obscure, and design development becomes intuitive. These problems suggest that the problem is not on the components themselves but on the way they interrelate.

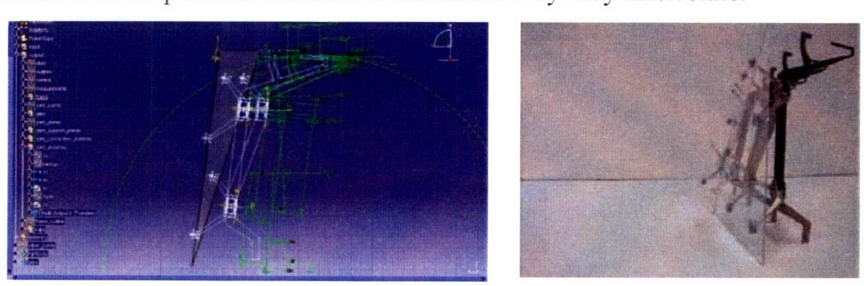


Fig. 3-8: 3D CAD and physical mockup

3.6.2 *Previous Work in Manufacturing and Systems Engineering*

Systems Theory is the science that deals with how components collaborate to build systems. Product Development, Industrial Management, and Manufacturing are disciplines that employ systems theory analysis tools to deal with modeling of both assemblies and production systems.

3.6.2.1 Network Analysis

Network analysis has been extensively applied to both assembly description and production systems planning. Assembly modeling has been thoroughly studied in manufacturing and Product Development using the *liaison graph* (Whitney, 2004). The liaison graph is a network whose nodes represent parts and connections represents liaisons. An assembly sequence can be explicitly defined as a series of nodes and liaisons. The liaison graph provides a concise and formal method to describe assemblies. Production systems' planning has been studied thoroughly by the Design Structure Matrix (Steward, 1981) by researchers such as Eppinger, Gebala, Smith, and Whitney (Eppinger, Whitney, Smith, and Gebala, 1994).

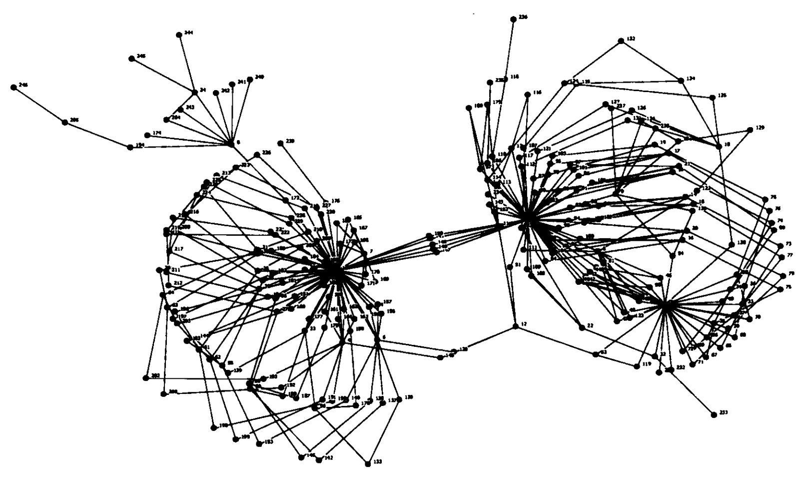


Fig. 3-9: The liaison graph of a V8 Engine

3.6.2.2 System Dynamics

System Dynamics is a methodology coming from Control Theory, originally developed by Jay Forrester (Forrester, 1961), for studying and managing complex feedback systems. A feedback system is a system in which information from result of past action is a basis for decisions that control future action. A System Dynamics model is a network consisting of: states (stocks); processes that affect states (flows); and decision variables that control processes. System Dynamics have been extensively used in modeling of supply chains to evaluate their performance.

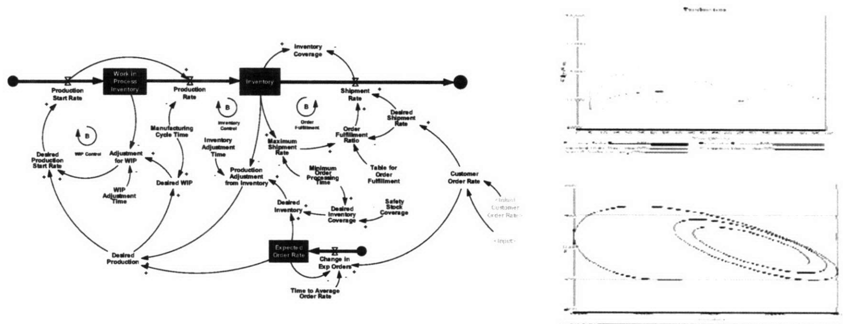


Fig. 3-10: A System Dynamics model of a supply chain and simulations.

3.6.3 *Differences between Network Analysis and System Dynamics*

While System Dynamics modeling and representation uses network analysis tools there are two differences that are of importance in this thesis. First, there is a difference in scope: network analysis deals with the structure of systems while System Dynamics deals with the dynamics of systems. Second, there is a difference in scale: network analysis explores structure of systems in detail often ending with networks with thousands of nodes. System Dynamics on the other hand takes a more abstract perspective and describes a system from a distance, without focusing on details.

3.6.4 *Problems with Previous Work in systems engineering*

While the liaison graph provides a formal way to study assembly structure and System Dynamics provide an effective way to simulate performance of supply chains it is still not clear how a liaison graph as a description of how and with which order the parts in a supply chain have to be put together could provide information on a System Dynamics model of the supply chain. Each method focuses on either the artifact or the production system but not on their correlation. In typical industrial supply chain for mass production where large numbers of widgets flow each day relating them with an assembly design is not an issue. System Dynamics describes production flow from an external perspective, often ignoring what flows inside the supply chain.

However a customized CAD/CAM project will produce a large number of custom parts coming from different locations that have to be delivered at specific timeframes in the construction site. It becomes obscure how to define the assembly and production rates in a system dynamics model. This information can be derived by the liaison graph. Therefore it would be useful to find a way to use assembly description in a System Dynamics model.

3.7 *New Model: Artifact-Value Chain*

The question is not how difficult an assembly design is but instead how difficult is for a specific value chain to deliver and assemble that specific design. As long as artifact's and value chain's structure are studied as different systems it is rather obscure to talk about feasibility of a system. Feasibility is a determination that a process, design, procedure, or plan can be successfully accomplished in the required time frame. Feasibility is a metric of a system that is trying to achieve a goal so it is necessary to describe the problem as a goal-seeking system.

It seems that if we want to evaluate performance of a value chain in delivering an artifact then we need a model that takes into account both artifact and value chain structure. If we had that model, then it would make more sense to measure its *feasibility* in achieving its goal.

4 HYPOTHESIS

4.1 Chapter overview

Chapter 4 presents the thesis question and my hypothesis, a proposal for addressing this question. *Can an artifact A be delivered by a value chain B, according to a design description C? If so, then how feasible is it?* Chapter 4 first decomposes the thesis question into two components: Assemblability of the design; and feasibility of the value chain. Assemblability deals with the structure of a system while feasibility deals with the dynamics of a system. This thesis speculates an approach that combines a structural description of the artifact into a dynamics description of the value chain.

4.2 Thesis question

This thesis deals with the following question:

In a Digital Fabrication Production System for planar part assemblies, can we tell if an artifact A can be delivered by a value chain B, according to a design description C? If so, then how feasible is it?

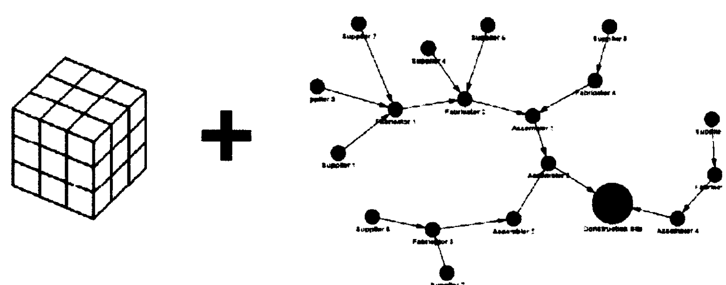


Fig. 4-1:The digital artifact and the digital value chain

4.2.1 Analysis of thesis question

Can an artifact A be delivered by a value chain B, according to a design description C? If so, then how feasible is it?

There are two issues to consider in this question: first, is the artifact design *assemblable*? Second, is the value chain able to efficiently deliver the design? Assemblability is a system's structure problem and can be studied through Network Analysis methods. Value chain feasibility is a system's dynamics problem and can be studied through System Dynamics. In short, this thesis deals with the study of structure and dynamics of a Digital Fabrication project. But what is the relation between structure and dynamics of systems?

4.2.2 *Dynamics is the behavior of structure.*

Structure and dynamics of a system are interdependent. Structure of the system affects its dynamics because it determines the way the components of the system interact. However, it is not clear how studying the structure of an assembly through the liaison graph may inform the building of a network model of the value chain. Moreover it is not clear how the network model of the value chain relates to a System Dynamics model of the value chain. It is reasonable to think that to be able to build a proper System Dynamics model of the value chain, first its structure must be mapped and understood. However if we could find a strategy to build a dynamic simulation model of the value chain, starting from the liaison graph we would be able to get a better understanding of the feasibility of the design.

4.2.3 *Mapping the structure*

The assembly sequence describes the order according which the parts will arrive in the construction site and the way according which the assembling processes will collaborate to deliver the artifact. Assembly sequence therefore provides the backbone of the value chain because it determines the scheduling of the rest of the upstream value adding processes. Assembly sequence can be derived by studying the liaison graph of the assembly. Therefore, starting from the liaison graph of the design and by following a reverse order to trace the value chain we can map the structure of the value chain and finally determine its dynamics.

4.2.4 *Hypothesis*

This thesis speculates that we should be able to tell if a value chain B can deliver an artifact A according to a design description C, if we could describe assembly structure of A as a liaison graph, value chain structure of B as a System Dynamics model, and find a way to execute A in B.

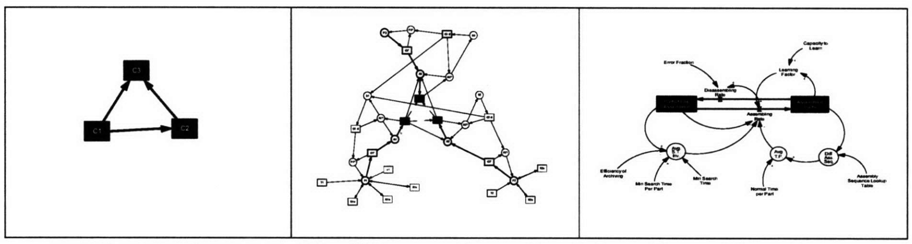


Fig. 4-2: The process: from liaison graph, to value chain, to System Dynamics

PART II - STEPS

Structure of part II

Part II is organized into four chapters: chapters 5, 6, 7, and 8.

- Chapter 5 explains concepts from systems that are used in the next chapters.

- Chapter 6 deals with the artifact and with design description methods of the artifact's structure. It presents two levels of description. The first is a method based on the liaison graph to describe, study, and debug planar part assemblies. The analysis aims first to verify that an assembly is possible, and second to define a valid assembly sequence. The second level of description is the CAD parametric description of the artifact. Finally, I present problems that arise with different levels of description. Examples demonstrate the method.

- Chapter 7 deals with the value adding process. It explain using System Dynamics how a value adding process follows and executes a design description and how the assembly sequence can affect the production rate of the value adding process. This part explains how System Dynamics can use a liaison graph. Examples demonstrate the method.

- Chapter 8 deals with the value chain. It integrates chapters 6 and 7 to build up the structure of the value chain and use it to simulate a system dynamics model of the project's performance. Moreover, it present how design dependency might cause conflicts in the value chain if it is different that the assembly dependency. Finally, it present some thoughts and ways of how this technique can be used to map and evaluate the entire value chain of an artifact. Chapter 8 ends with an example of a value chain.

5 SYSTEMS

Definitions

5.1 *Chapter overview*

Chapter 5 explains concepts from systems that are used in the next chapters.

5.2 *Definition*

Systems are sets of interrelated *components* that together achieve a *purpose* which cannot be achieved by any component by itself. A system has a *goal, architecture* and *function.* Goal determines what the system is meant to accomplish. Architecture determines how the components are connected to deliver the goal and is studied through *structure*. Function, determines how the components *interact* in time to deliver the goal and is studied through *dynamics*. Systems are separated by the rest of the world by their *boundary*. Anything that enters this boundary is an *input* and anything that exits the boundary is an *output*. Output is a function of input. A component can be a primitive *module* or a *subsystem* by itself. As a consequence any group of components can be clustered into a subsystem.

5.3 *Structure*

Structure, determines how the components connect to each other. Structure can be modular, integral, hierarchical or non-hierarchical.

5.3.1 *Modularity*

Modular systems are systems whose components can be clustered in such a way that in each cluster the components have higher connectivity than the clusters themselves. Integral systems are systems that cannot be decomposed into clusters because all the components are highly connected. Modular assemblies are the assemblies that can be decomposed into subassemblies such as the engine of a car. Integral assemblies are assemblies that cannot be decomposed into subassemblies because all parts are functioning together, such as the wing or the hull of an airplane.

5.3.2 *Hierarchy*

Hierarchical systems are systems in which the relation between components is directed. Constraint-based modeling and assemblies are examples of hierarchical systems.

5.4 *Dynamics*

Dynamics determine how the values of the components of a system change in time to deliver the goal. Dynamic systems are systems that change in time or systems whose output is a function of input and time. *Feedback systems* are hierarchical dynamic systems with non linear behavior whose future action depends on results from past action. The fundamental structural element of a feedback system is the *feedback loop.* A feedback loop exists when a component up in the hierarchy depends on a component down in the hierarchy.

5.5 *Ability - Feasibility*

Ability of a system to achieve its goal relates to its structural integrity. Feasibility of a system in achieving its goal relates to its dynamics.

5.6 *Representation*

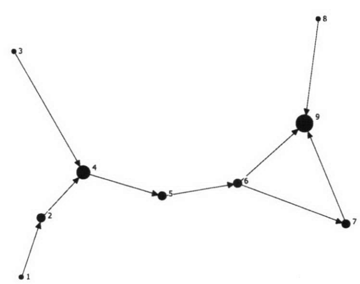
5.6.1 *Network Representation*

The structure of a system is represented by a network –or graph- whose nodes represent the components of the system and links represent the relations between these components. The network can be directed or non-directed according to whether the system is hierarchical or not.

Bipartite networks are networks consisting of two types of nodes. In bipartite networks links are allowed only between nodes of different type. From a bipartite network two simple networks of one type of nodes can be derived by the following rule: in each derived network two nodes will be connected if and only if they connect to the same node of the other type in the bipartite network. Similarly, there are tripartite networks etc.

5.6.2 *Matrix Representation*

Another way to represent the structure of a system is with a matrix. The matrix of a graph with n nodes is an n*n matrix whose columns and rows represent the nodes of the network in the same order. A mark in column *i* and row *j* represents a link from node *i* to node *j*. This means that in order to find the precedents of node *j* we first trace row *j* and record all marks that we find; then we identify the nodes that correspond to the columns of these marks. Similarly, to find the decedents of node *j* we have to trace column *j* and record the rows that correspond to marks that we find. Typical representation matrices are the adjacency matrix and the Design Structure Matrix (DSM). The adjacency matrix is a matrix in which marks are 1s or 0s according to whether they represent a link or an absence of a link. Adjacency matrix therefore captures structure of a system but not values of components. The DSM, developed by Donald Steward,[3] can have various marks representing values.



	1	2	3	4	5	6	7	8	9
1	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	1	1	0	0	0	0	0	0
5	0	0	0	1	0	0	0	0	0
6	0	0	0	0	1	0	0	0	0
7	0	0	0	0	0	1	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	1	1	1	0

Fig. 5-1: Network representation and adjacency matrix of a system

5.7 *Degree of a Node*

In a non directed network the degree of a node denotes the number of connections that this node has with other nodes in the network. In directed networks each node has an in-degree and an out-degree. In-degree of a node denotes the number of links that point from neighbor nodes to the node.

[3] **Steward, Donald V. *Systems Analysis and Management: Structure, Strategy and Design.* Petrocelli Books, 1981.**

Out-degree of a node denotes the number of links that point from the node to neighbor nodes.

5.7.1 *Input/output of a node*

A node is endogenous to the system if both its in-degree and its out-degree are at least 1. If its in-degree is equal to 0 then the node is exogenous to the system. If an endogenous node has out-degree equal to 0 then that node is an output. If an exogenous node has in-degree equal to 0 then that node is an input.

5.7.2 *Difficulty/importance of a node*

Since in a hierarchical system every component is explicitly defined by its predecessors, a node will be valid if and only if all of its predecessor nodes are valid. Following this, a node is difficult to achieve if it has a high in-degree. On the other hand, a node is important if it has a high out-degree, because it distributes its input to many other nodes. This is generally the case in task networks. Therefore by studying the nodal degree distribution in a directed network we can get an idea about its behavior.

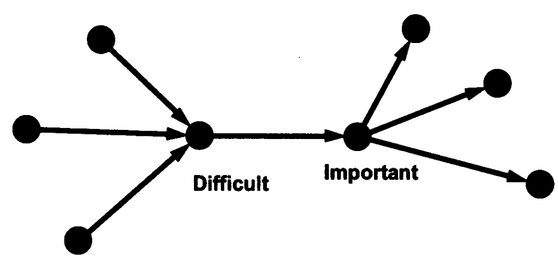


Fig. 5-2: Difficulty and importance of a node as a function of its degree.

5.8 *Semantics of Systems*

Deciding what the nodes and links of a network represent is a modeling decision and depends on the purpose of the system and on the properties of the system that are of importance to the modeler. Many modern modeling languages such as the Object Oriented Modeling (OOM) language **(Rumbaugh, Blaha, Premerlani, William, Eddy, and Lorensen, 1991)** or the Object Process Methodology (OPM) model (Dori, 2002) the world as consisting of objects and processes. Even the structure of many human languages is based on nouns and verbs. Having a robust modeling language is important for defining the problem of study and understanding a solution strategy.

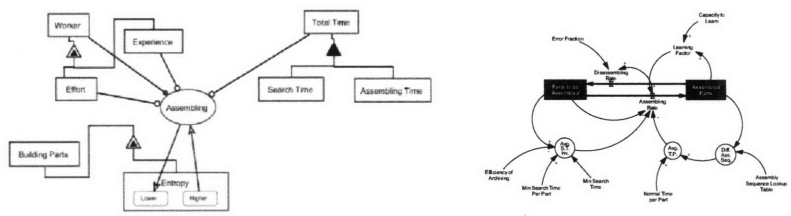


Fig. 5-3: An assembling system in OPM and System Dynamics.

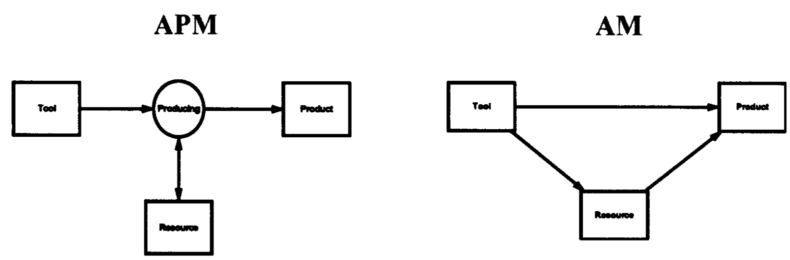
Evaluating the performance of a system implies first that the system has a clear goal and a function; second, that there are at least some components in the system that they carry its functional requirements to achieve the goal. Typically these functioning components are called *processes*. For example if we want to evaluate the performance of an assembly sequence it would be helpful to describe the problem in terms of assembling processes and parts.

5.9 The Attribute Process Methodology (APM)

To explain the relation between structure description methods (such as the liaison graph) and dynamics description methods (such as System Dynamics), I propose the Attribute Process Methodology framework; a modeling language consisting of attributes and processes. The APM is motivated by OPM but the difference is that OPM focuses on objects while APM focuses on attributes. In APM an object is a collection of attributes. We perceive objects only through their attributes therefore the concept of an object is a logical conclusion of the observer. For this reason expressing an object is redundant for this study. In the following, I will be using APM to describe several examples.

5.9.1 *APM Representation*

APM is a modeling framework based on a bipartite network. APM has only two entities: attributes and processes. As it is the case with bipartite networks attributes can connect only to processes but not to other attributes. Similarly, processes cannot connect to other processes. However, from a bipartite APM network two networks can be extracted: a process network, and an attribute network.



Process **Producing**:
Produces **Product**
Uses **Tool**
Affects and is affected by **Resource**

Product is produced by **Tool** and **Resource**
Tool operates on **Resource** to produce **Product**

Fig. 5-4: APM and AM representation of a production process,

In APM processes are represented as circles and attributes as boxes. A unidirectional link from a source node to a destination node means that the source modifies the destination. A bidirectional link means mutual effect. For example if a process uses a tool then a unidirectional link exists from the tool to the process; the process is affected by the tool but the tool is not affected by the process. If however the process uses a resource, the link is bidirectional; the process uses the resource by consuming it, and the resource modifies the process.

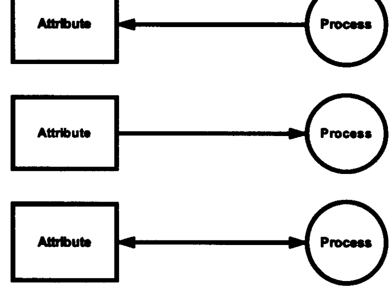


Fig. 5-5: relations between attributes and processes in APM

5.10 Production System

This thesis defines a production system as follows:

A production system is a set of collaborating fabrication, distribution and assembly processes that use tools and resources to produce an artifact according to an input design at a specified location, time, and cost.

Using APM this thesis defines a production system as follows:

A production system is a feedback system whose goal is to match a set of artificial attributes to a set of design attributes. Artificial attributes are modified by a set of value adding processes. Design attributes are modified by a set of design processes.

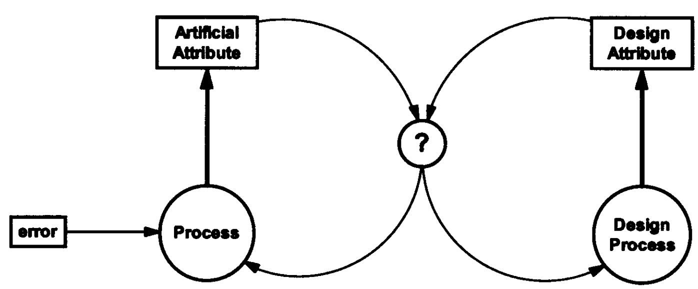


Fig. 5-6: Conceptual feedback model in APM of a production system.

The set of possible designs that can be produced is limited by tool, resource, and collaboration constraints. Production processes are divided into value adding and non value adding. A value adding process is a production process that embeds design information to an artificial attribute. A non value adding process is a production process that does not embed design information to an artificial attribute but it is necessary for a value adding process to function. An example of a value adding process is a fabrication process. An example of a non value adding process is a transportation process.

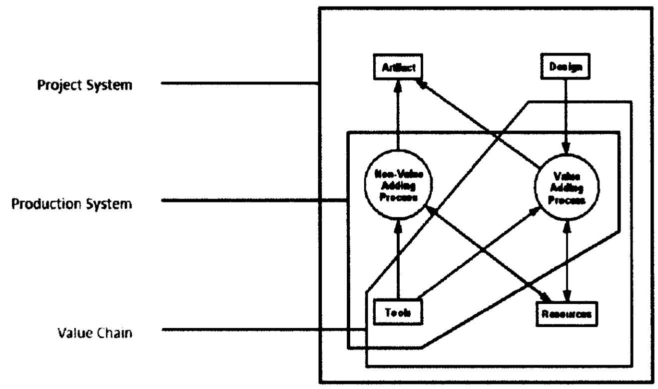


Fig. 5-7: structural description of a production system in APM

6 THE ARTIFACT

Structure

6.1 *Chapter overview*

Chapter 6 deals with the artifact and with design description methods of the artifact's structure. It presents two levels of description. The first is a method based on the liaison graph to describe, study, and debug planar part assemblies. The analysis aims first to verify that an assembly is possible, and second to define a valid assembly sequence. The second level of description is the CAD parametric description of the artifact. Finally, I present problems that arise with different levels of description. Examples demonstrate the method.

6.2 *Artifact*

An artifact is a *system* of *artificial attributes* that will be produced in the natural world as reflections of *design attributes* in the design world. An artificial attribute is an attribute made by a human process, such as geometry, color, etc. The artifact therefore exists in combination with a design description. The artifact can be simple or compound depending on the number of its artificial attributes and on the level of desired abstraction in the description. An artifact is delivered by a value chain, which is a directed network of value adding processes.

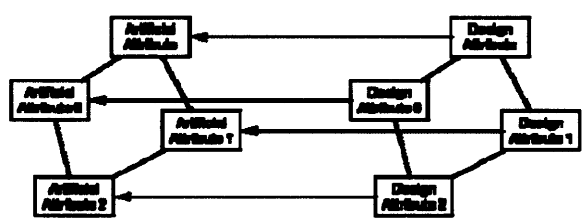


Fig. 6-1: the artifact as an association of artificial and design attributes

6.3 *Assembly*

An assembly is a subsystem of an artifact. An assembly is a system of parts connected through liaisons whose goal is to deliver one or more *key characteristics (KC).* A KC is a requirement that the assembly must meet such as a minimum distance or a contact point between two parts. A formal definition of an assembly is given by Whitney: *"An assembly is a chain of coordinate frames on parts designed to achieve certain dimensional relationships, called key characteristics, between some of the parts or between features on those parts".* [4]

6.3.1 *Constraint delivery*

Each part in the assembly is constrained by its predecessor parts in the assembly sequence. Therefore every assembly has a root part from which the assembly sequence starts. Each liaison removes one or more degrees of freedom from the part it locates. Therefore each arc in the liaison graph is assigned a value that corresponds to the number of degrees of freedom it constraints. Each node in the liaison graph needs to have zero degrees of freedom in order that the part is properly constrained. If the number of degrees of freedom that the liaisons cancel is more than six, then the part is over-constrained; if it is less than six then the part is under-constrained; finally if it is six, then the part is properly constrained. Therefore an assembly process can be conceived as a gradual cancellation of the degrees of freedom of the parts.

6.3.2 *Planar Part Assemblies*

A planar part assembly is an assembly whose parts are flat interlocking sheets of material. Three-axis CNC routers cut planar parts perpendicularly to their plane, constraining the cuts to have 90-degree bevel angles. Therefore, two parts can have a connection if and only if they are coplanar or perpendicular.

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[4] **Whitney, Daniel E. *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development*. Oxford University Press, USA, 2004.**

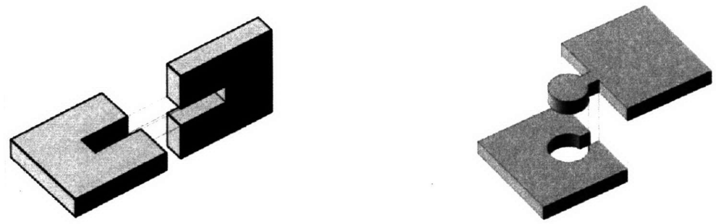


Fig. 6-2: The basic connections of two planar parts.

This thesis assumes that a connection between two perpendicularly interlocked parts constrains 5 degrees of freedom. In a real planar part assembly that would not be the case because two interlocking parts could rotate along their intersection axis. However, in reality planar parts have thickness because of the material used and therefore they cannot rotate around their intersection axis. The only degree of freedom that is left is the one of the installation direction of the one part to the other.

6.4 *Description of the Artifact*

In this thesis a design description is defined as a mapping between a set of artificial attributes and a set of design attributes. It is a system of design attributes that can be hierarchically associated or non-hierarchically associated. Purpose of a design description is to drive a value adding process. This thesis deals with 2 different levels to describe the artifact: The Assembly Description which describes actual constraint delivery between parts in the assembly, and the Parametric Design Description, which describes parametric constraint hierarchy between parts. These two levels differ in the way they associate the components of the artifact. The liaison graph drives the assembling process; the CAD graph drives the fabrication process.

6.5 *Assembly Description*

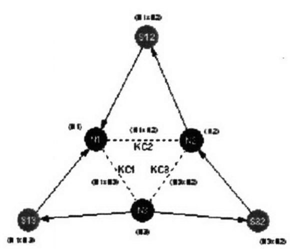
The Assembly Description describes actual constraint delivery between parts in the assembly and it is studied through the liaison graph and the corresponding adjacency matrix.

6.5.1 *Liaison Graph*

The liaison graph is a directed acyclic graph whose nodes represent parts and arcs represents liaisons (fig. 6-3). Direction of arcs indicates order of constraint delivery between two different parts. A dashed non-directed link represents a Key Characteristic. In a liaison graph no cycle is allowed since that would mean that a part constrains itself through a chain of constraint deliveries. The liaison graph provides a concise and formal method to understand assemblies.

6.5.2 *Adjacency Matrix of Liaison Graph*

A liaison graph is represented by its corresponding adjacency matrix (fig. 7-3).



CONSTRAINTS MATRIX						
	N3	S13	S23	N2	S12	N1
N3	0	0	0	0	0	0
S13	1	0	0	0	0	0
S23	1	0	0	0	0	0
N2	0	0	1	0	0	0
S12	0	0	0	1	0	0
N1	0	1	0	0	1	0

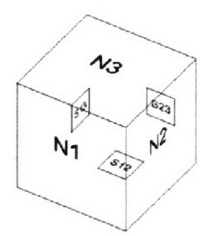


Fig. 6-3: The liaisong graph and adjacency matrix of an assembly of six parts

6.5.3 *Assembly Sequence*

An assembly sequence is a way to trace the liaison graph from precedent nodes to decedent nodes, such that the Key Characteristic can be achieved. Not any ordering of the nodes is a valid assembly sequence. The difficulty of each step relates to the in-degree of the node which indicates the number of simultaneous liaisons that must be achieved during that step. For example a part will be more easily connected to another part if it has one liaison rather than if it had multiple liaisons. In an assembly sequence the sequence of the in-degrees indicates the difficulty in time of the assembling process. Therefore, it is expected that the assembling rate would drop in a node with high in-degree. By describing an artifact through its liaison graph we can get an understanding of the inherent difficulty of its assembly.

6.5.4 Representation of Assembly Sequence in the Adjacency Matrix

In the adjacency matrix an assembly sequence can be represented as an ordering of the rows and columns. Such ordering can be derived by rearranging the rows and columns of the adjacency matrix so the resulting matrix has all its marks below the diagonal (fig. 6-3). The sequence of the sum of each column gives the list of the in-degree distribution of the assembly sequence. The in-degree distribution describes the difficulty of the assembly sequence because it indicates the number of liaisons each newly inserted part needs to achieve with the rest of the existing assembly.

6.5.5 Representation of Planar Part Assemblies

Since the parts are planar, each part can be represented by a normal vector perpendicular to its plane. The normal vector values can be assigned as values of the nodes in the liaison graph of the assembly. Evaluating an assembly therefore can be done by looking for inconsistencies between values of neighbor nodes in the liaison graph. The values of the normal vectors of the parts and of the liaison vectors of the liaisons can be inserted in the adjacency matrix of the assembly.

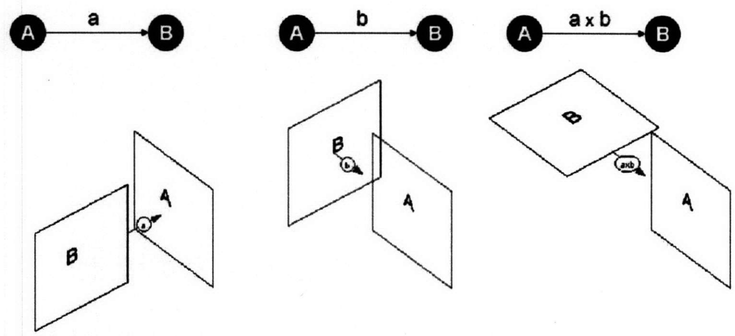


Fig. 6-4: The 3 liaison types for planar part assemblies

6.5.6 *Assemblability Rules of planar Part Assemblies*

I briefly present the following rules regarding planar part assemblability:

1. A planar part can be represented by the normal vector of its plane. In the liaison graph the node representing the part has the normal vector as a value.
2. A liaison between a locating part A and a located part B can be represented by the installation vector $\overrightarrow{ab}$ of part B to part A. In the liaison graph, the arc representing a liaison has the value of the vector and the direction from the locating part A to the located part B. In the liaison graph a liaison is represented by a solid line.
3. An Adjacency Key Characteristic (AKC) between two adjacent parts A and B is the cross product vector of A and B and it indicates the direction of the edge between A and B. in the liaison graph an AKC is represented by a dashed line.
4. Two nodes can be connected by a liaison if and only if the cross product of their normal values is 0 or 1. If it is 0 then the parts are perpendicular; if it is 1, then the parts are coplanar.
5. If two parts A and B, with normal values of *a* and *b* respectively, are perpendicular, then there are 3 liaison types to connect part B to part A: $\vec{a}$, $\vec{b}$, $\overrightarrow{axb}$. Type 1 means that the second part connects to the first part along the direction of the normal vector of the first part. Type 2

means that the second part connects to the first part along the direction of the normal vector of the second part. Type 3 means that the second part connects to the first part along the direction of the cross product of their normal vectors (figure 6-4).

6. Difficulty of an assembly step is determined by the number of links an installed part has with the rest of the subassembly. This is equivalent to the in-degree of that part.
7. A subassembly is a cluster of two or more parts connected by liaison graphs. A subassembly can be represented as a single part.
8. A part can be located by another part by one or more liaisons. If the liaisons are more than one then their vectors must be parallel.
9. Two parts can be connected by a third part which is perpendicular to them. The third part has a normal value equal to the cross product of the two parts.
10. If in one part more than one liaisons end, then this part can be installed only after all previous parts have already been installed.
11. If a part has only out-degree but not in-degree, then this part is a start.
12. If a part has only in-degree but not out-degree then this part is an end.

6.6 Applications

6.6.1 Constructing an assembly from the KC graph

For any pair of adjacent parts that are linked by a Key Characteristic a third part perpendicular to both first parts can be defined. Therefore starting by a graph with the Key Characteristics we can generate a new liaison graph by adding new nodes.

Example

Let N1, N2, N3 be planar parts, with normal vectors $\overrightarrow{N1}$, $\overrightarrow{N2}$, $\overrightarrow{N3}$, respectively (fig. 7-5). The 3 parts have to be connected along their common edges by pairs of two (N1-N3, N1-N2, N2-N3). We want to define an assembly that will achieve these KC's. To do that, we need to define connecting parts (interfaces), their orientations and their liaisons so that there is a valid assembly sequence.

6.6.2 *Finding an Assembly Sequence*

An assembly sequence is a path that traces all the nodes in the liaison graph. In a valid assembly sequence every node must have incoming liaisons of the same type so that they are parallel. Therefore to find a valid assembly sequence we start testing all possible ways to trace the liaison graph; on every step we select one of the 3 possible liaison types and verify that all incoming liaisons are of the same type (a, b, or axb).

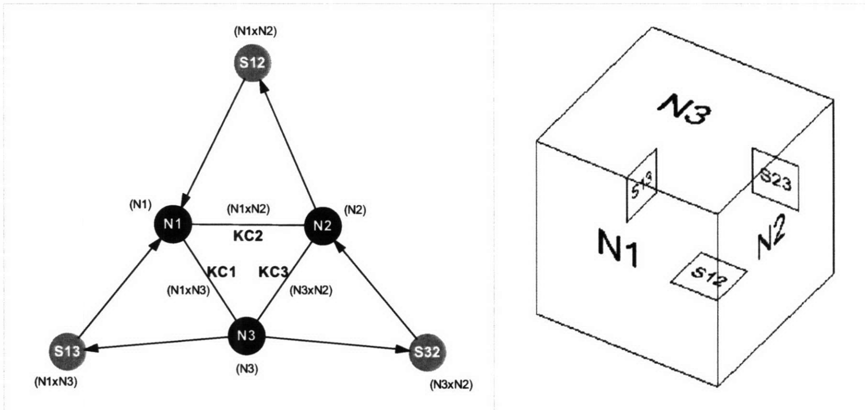


Fig. 6-5 Liaison graph and geometric configuration of a 6-part assembly.

	N3	S13	S23	N2	S12	N1
N3	**N3**	0	0	N3xN2	0	N3xN1
S13	N3	N1xN3	0	0	0	0
S23	N3	0	N2xN3	0	0	0
N2	N2xN3	0	1	**N2**	0	N2xN1
S12	0	0	0	N2	N1xN2	0
N1	N1xN3	N1	0	N1xN2	N1	**N1**

Table 6-1: The associations' matrix shows the relations between the three initial parts N1, N2, and N3, and the associated A13, S23, S12 interfaces.

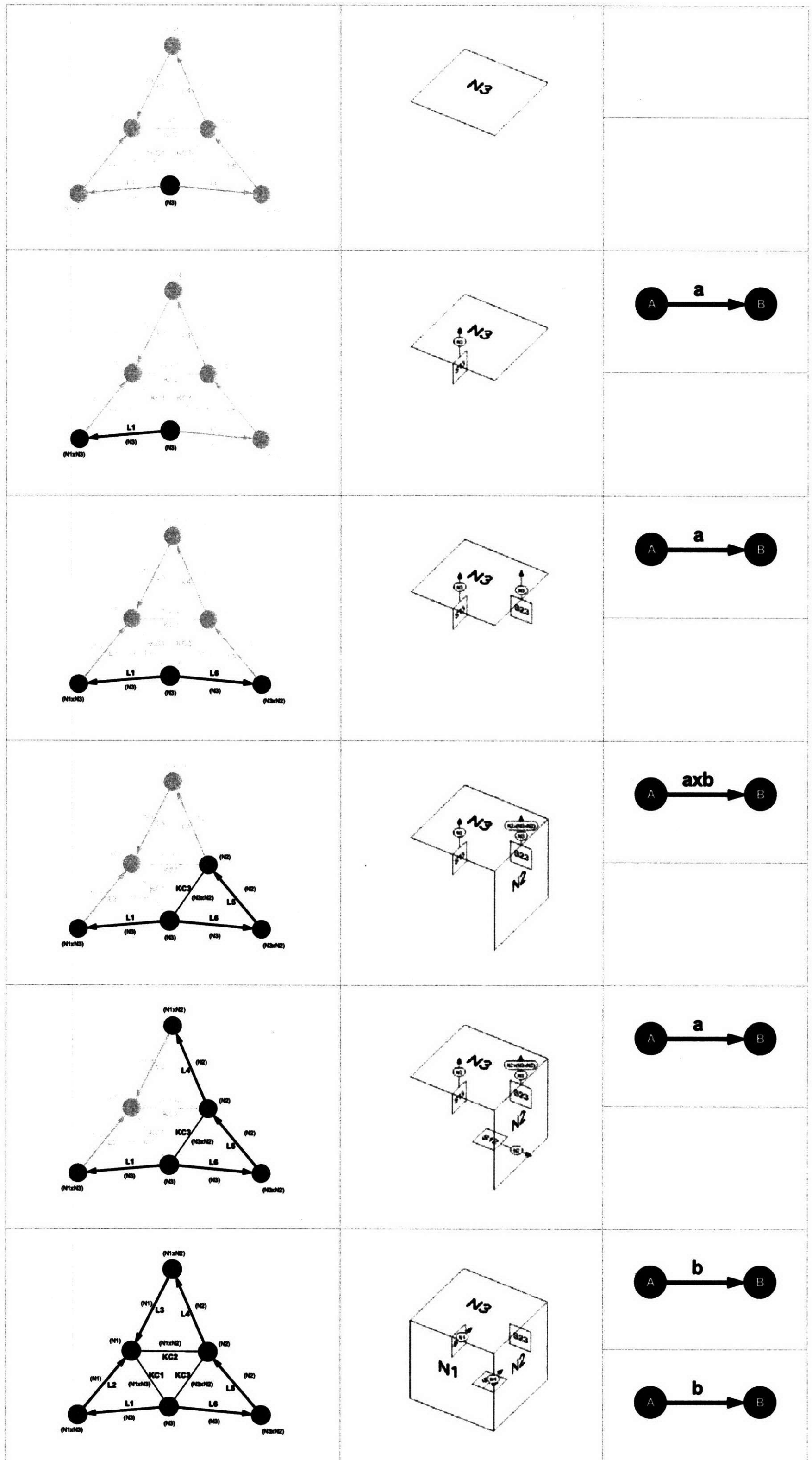


Table 6-2: Example of a Valid Assembly Sequence

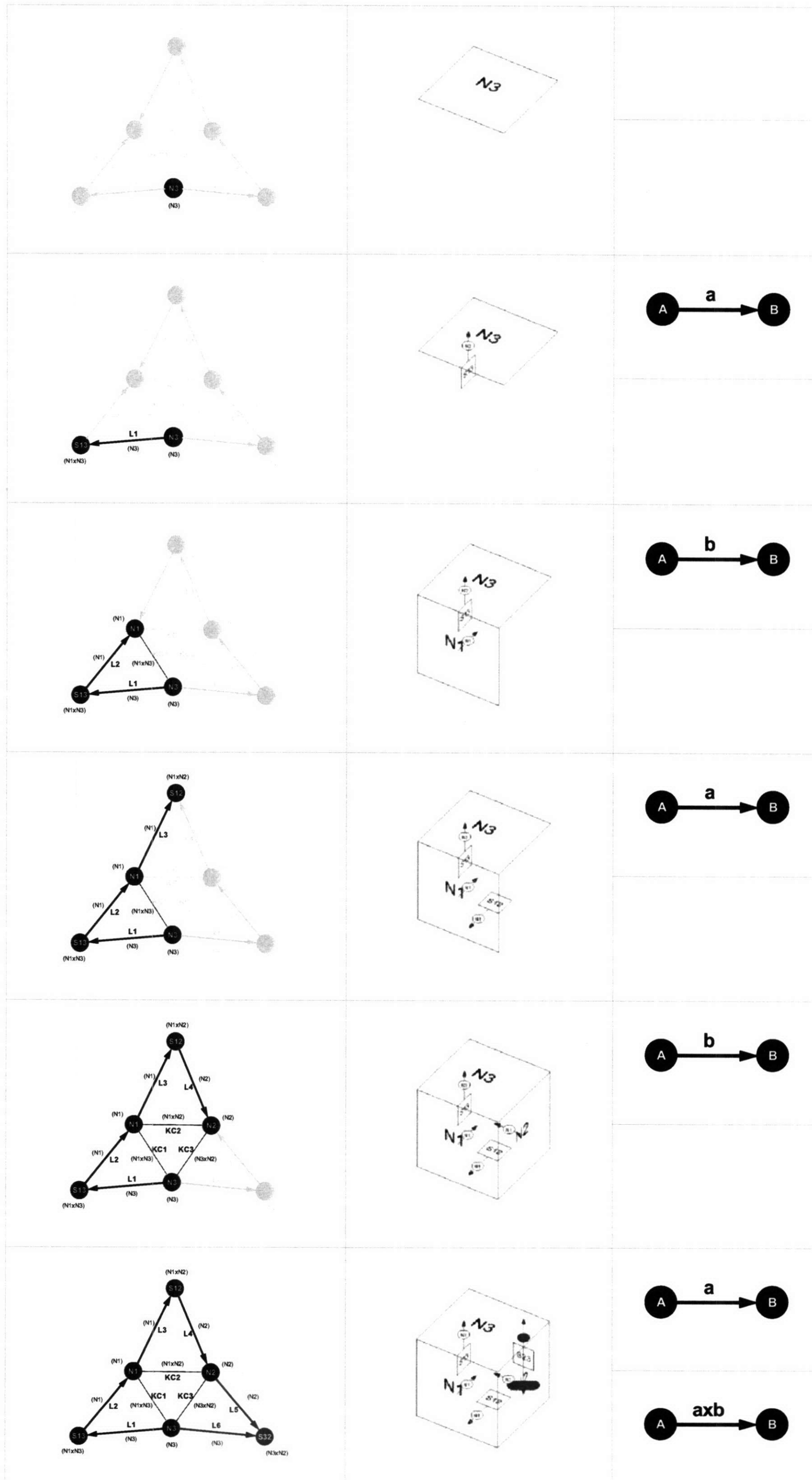


Table 6-3: Example of a Non-Valid Assembly Sequence

6.7 *Experiment 1: Assembly Failure in a chair*

The following experiment refers to the design, fabrication and assembly of a chair[5] made from interlocking planar parts. The chair was designed in 3D CAD modeling software (Rhinoceros V4.0) and the parts were fabricated from 1" plywood sheets in a 3-axis CNC router. The assembly consisted of 29 interlocking pieces of plywood: 16 where horizontal and 13 where vertical. Modeling of the assembly focused on representing two states of the artifact: the assembled form where all parts are put together and the flattened parts in cut-sheets for fabrication. The assembled form seemed to be a valid configuration of the artifact with no clashes between the solid volumes of the parts. Unfortunately, assembly process stopped at a certain point; installation of parts was impossible due to conflicts in the installation vectors. The designers had no tools to describe, understand, and evaluate the assembly process.

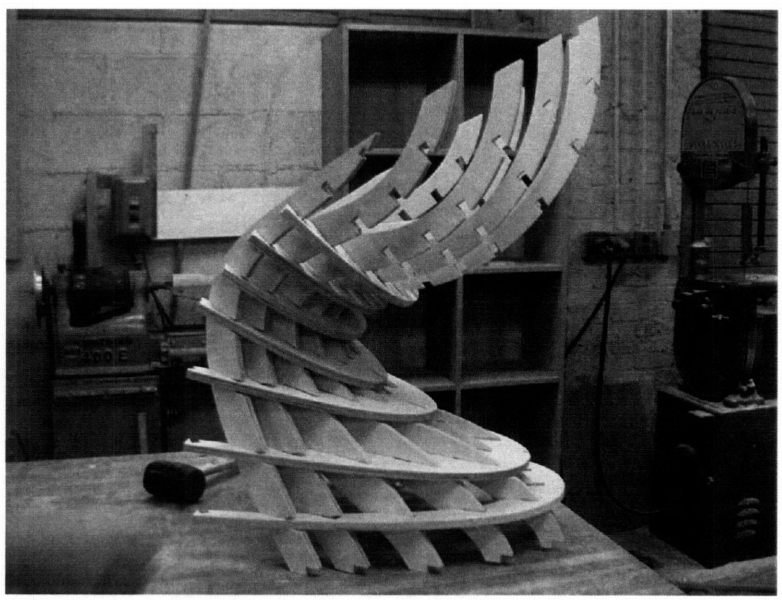
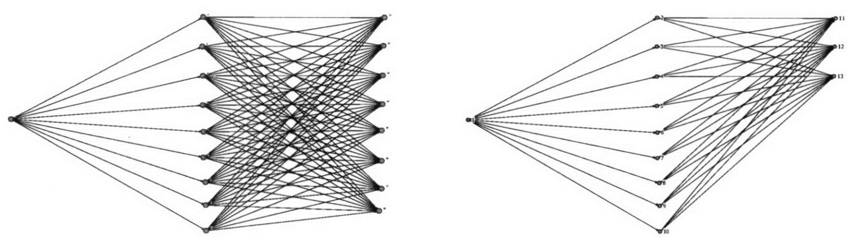


Fig. 6-6. Manual assembly jammed on eighteenth part

[5] Team project in class *4.580: Inquiry into Computation and Design* (Prof Terry Knight, Prof Lawrence Sass), Massachusetts Institute of Technology, fall 2006. Team members: Joshua Lobel, Magdalini Pantazi, Dimitris Papanikolaou.

A representation of the assembly with the liaison graph clearly shows that the assembly sequence is in fact impossible due to installation vector incompatibility between parts (Fig. 6-7). For simplicity this liaison graph represents a similar assembly of 18 parts: 9 horizontal and 9 vertical. All liaisons are type 3 liaisons (rule 5). From the liaison graph we can have a formal understanding of the assembly sequence: the first part can be any horizontal or vertical member; in the experiment we selected the 6th horizontal member from the bottom. In the liaison graph, the next 9 pieces can be easily installed by one liaison each. However, starting from the 11th part all other parts need to achieve 9 simultaneously non-parallel liaisons; this is impossible.

The analysis shows that assembly should jam at the eleventh step because after that each next part would have to simultaneously connect with nine non-parallel installation vectors with the rest of the assembly. However, real assembly jammed later due to the looseness of the notches of the parts.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
3	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
5	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
6	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
7	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
8	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
9	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
10	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 6-7: Left: The complete liaison graph of the chair. Right: the actual liaison graph when the assembly sequence jammed. Bottom: Adjacency matrix.

6.8 *Parametric CAD Description*

The Parametric CAD Description describes parametric constraint hierarchy between parts and is studied through the CAD graph and the CAD Constraints Matrix. The CAD graph is a directed acyclic graph whose nodes represent design attributes and arcs represents parametric associations between them. The CAD graph and the liaison graph can be different for the same artifact. For example a house which rests on the ground and supports a roof will have an assembly constraint delivery from the ground to the walls to the roof, while its parametric constraint delivery could be from the ground to the wall and from the roof to the wall.

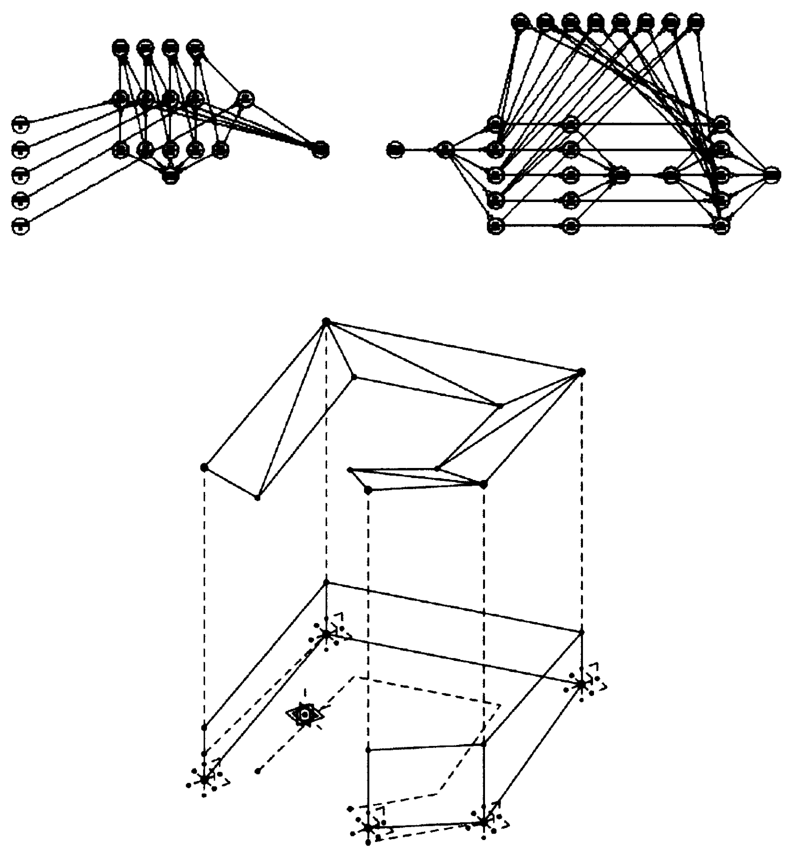


Fig. 6-8: CAD graph of a roof that rests on a wall.

6.9 *Conflicts between Assembly and CAD Description*

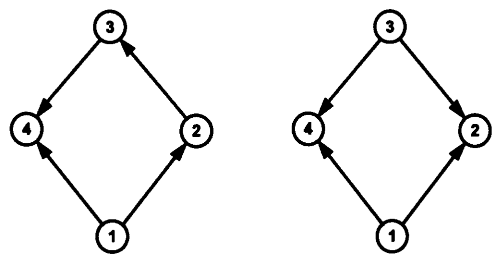
When two design descriptions describe the same set of attributes associating them in a different way, problems may arise if these two descriptions guide different value adding processes that operate on the same set of attributes. For example, consider an artifact of four parts [P1, P2, P3, P4]. The assembly constraint delivery order is the following: P1 constrains P2; P2 constrains P3; P1 and P3 constrain P4. The assembly sequence is: P1, P2, P3, and P4. The CAD constraint delivery is the following: P1 and P3 constrain both P2 and P4. Production process will follow the assembly sequence. Consider that error factors of value adding processes introduce noise in the artificial attributes so that they do not match with the corresponding design attributes. For example fabrication of P3 is slightly different than P3'. When P3 needs to be located on P2 the two parts do not fit. P3 therefore would have to be fabricated again measuring the existing parts P1 and P2 that constrain P3, and updating the CAD description that controls fabrication. However in the CAD description P3 constrains P2 and not the opposite; therefore it is impossible to update P3 according to the new measurements of P2. These are typical problems that arise in description inconsistencies. Such inconsistencies are dealt with tolerance allocating between part interfaces. It is therefore important to locate these points of inconsistency and take into account for sufficient tolerance allocation.

6.9.1 *Dependency of Assembly Processes on Fabrication Processes*

A value chain consists of fabrication and assembly processes that follow design descriptions. Assembly processes depend on fabrication processes, in the sense that if a part is erroneously fabricated then it will be erroneously located as well. Ideally, a digital fabrication value chain consists of digital fabrication processes and manual assembly processes; therefore the assumption is that there is a minimum risk of error. However, in reality a digital fabrication value chain has always some manual fabrication processes, and usually these are always first in the assembly hierarchy. For example, an assembled structure will have to be founded on the ground, and the excavation as well as foundation processes are manually controlled.

6.9.2 *Identifying Points of Risk for Tolerance Allocation with the Design Structure Matrix*

Superimposing the CAD constraints matrix on the assembly adjacency matrix in one Design Structure Matrix may reveal inconsistencies that could possibly cause problems in a project. The matrix is ordered according to the assembly sequence. In the following example we can clearly from the Design Structure Matrix see that part 3 is the only part whose assembly and parametric dependencies are different.



	1	2	3	4
1				
2	D A		D	
3		A		
4	D A		D A	

Table 6-4: Left: Liaison graph. Middle: CAD graph. Right: Compound DSM

In the compound Design Structure Matrix a mark with the character "D" denotes a design dependency, while a mark with the character "A" denotes assembly dependency. For example parts 2 and four depend both in terms of design and assembly on part 1. Part 3 however depends on part 2 only in terms of assembly but not in terms of design. Therefore, if an error occurs in the liaison link between parts 3 and 2, then part 3 will not be able to be redesigned based on measurements of part 2. By using the compound DSM we can identify groups of parts that have particular risk because if an error occurs in one of these parts then it will be difficult to correct it.

7 THE VALUE ADDING PROCESS

Dynamics

7.1 *Chapter overview*

Chapter 7 deals with the value adding process. It explain using System Dynamics how a value adding process follows and executes a design description and how the assembly sequence can affect the production rate of the value adding process. This part explains how System Dynamics can use a liaison graph. Examples demonstrate the method.

7.2 *Value Adding Process*

A value adding process is a production process that modifies an artificial attribute to match it to a design attribute. Equivalently, a value adding process is a process that executes a Design Description to modify a set of artificial attributes. In a Digital Fabrication value chain there are two types of value adding processes: fabrication and assembly processes. A fabrication process will follow a Parametric Design Description to fabricate a part. An assembly process will follow an Assembly Design Description to locate the parts on existing ones.

7.2.1 *Performance of a Value Adding Process*

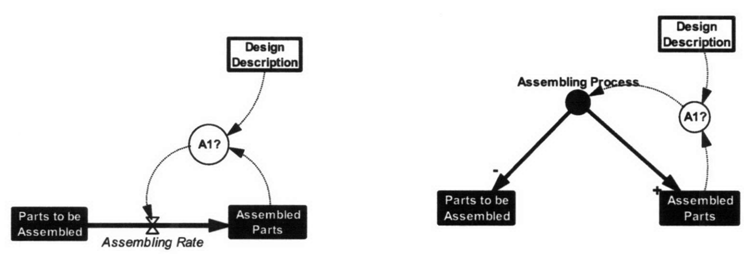
The basic module to study dynamics of a value chain is a feedback system of a value adding process, the artificial attribute it modifies, the design attribute it tries to match to, and a decision function that controls the process. Feasibility of the value adding process is a function of time, cost, and goal accomplishment.

7.2.2 *System Dynamics Modeling*

System Dynamics modeling consists of stocks and flows. Stocks are like bathtubs, and flows are like pipelines connecting the bathtubs. Simply stated, System Dynamics studies the flow of water in the pipelines and the bathtubs. Stocks represent attributes and flows represent processes. Flows modify stocks positively or negatively in the same sense that processes modify attributes when applied to them. A System Dynamics model is simulated in time and the values of its components change by differential increments.

7.2.3 *Artificial Attribute*

Selecting the type of the artificial attribute that a value adding process modifies is a modeling decision and it depends on the attributes that are important in describing the system. To evaluate performance, the artificial attribute needs to be quantifiable. For example, a digital fabrication CNC cutting process may modify the artificial attribute that is defined as the ratio of the perimeter of a part divided by its area. Similarly, an assembling process can modify either the degrees of Freedom (DOF) of the installed part or the number of liaisons of the installed part with the rest of the assembly. In this thesis I determine an assembling process as a System Dynamics model of a process that creates liaisons to a stock of parts following the in-degree distribution along a predefined assembly sequence.



System Dynamics APM

Fig. 7-1: System Dynamics and APM representations of a feedback system

7.2.4 *Building a System Dynamics Model of an Assembling Process*

Consider the following system in APM: an assembling process P assembles two parts A, and B (fig. 8-1). in the APM the modeled attributes are the in-degrees of the parts. A' and B' are the start attributes, before the assembly process connects them. A and B are the end attributes, after the assembly processes P1 and P2 connects them. A" and B" are the design attributes, which are the goals of the two assembling processes P1 and P2. t1 and t2 are the times of P1 and P2 respectively. In the first time frame P1 modifies A from A' to match it to A" by the decision function '?1'. When A matches A" the decision function '?1' passes control to decision function '?2' that controls assembling process P2. P2 uses A to modify B' to B to match it with B".

In the System Dynamics model both A' and B' constitute the Start Stock of the assembling process; A and B constitute the End Stock of the assembling process; A" and B" constitute the goal of the system. The flow from '?1' to '?2' constitutes the flow in a System Dynamics model. The APM model is equivalent to the System Dynamics model shown in figure. The difference is that the APM is a model in which all timeframes are represented as different states while in a system dynamics model the timeframes iterate in the timeline. The Design Description is the sequence of the in-degrees of the nodes, which is [0,1]. Since a System Dynamics model is a collapsed Attribute Process model, we can use the nodal degree distribution to determine the assembling rate (flow).

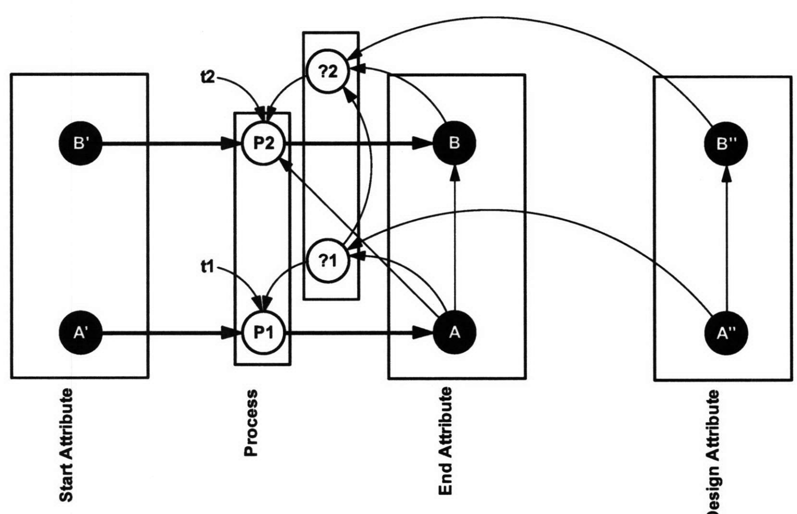


Fig. 7-2: Complete APM model of an assembly process of 2 parts

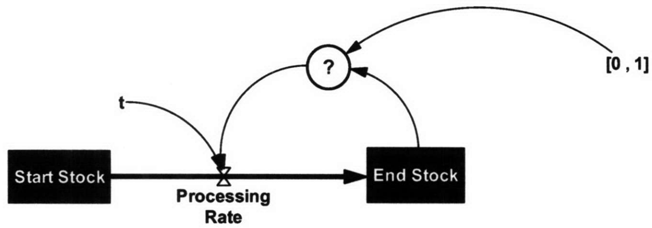


Fig. 7-3: The corresponding System Dynamics model of the assembly process of 2 parts

7.2.5 *Experiment: Façade Panel*

The second experiment refers to the design, fabrication, and assembly of a mockup of a façade panel[6]. Design development took place in a parametric 3D CAD modeling software (CATIA V5 R18). In this case, while the assembly was successful, it proved to be difficult, and took significantly more time than the designer expected. While this example is relatively simple, including a small number of parts, it clearly demonstrates the lack of tools that designers need to understand assembly process.

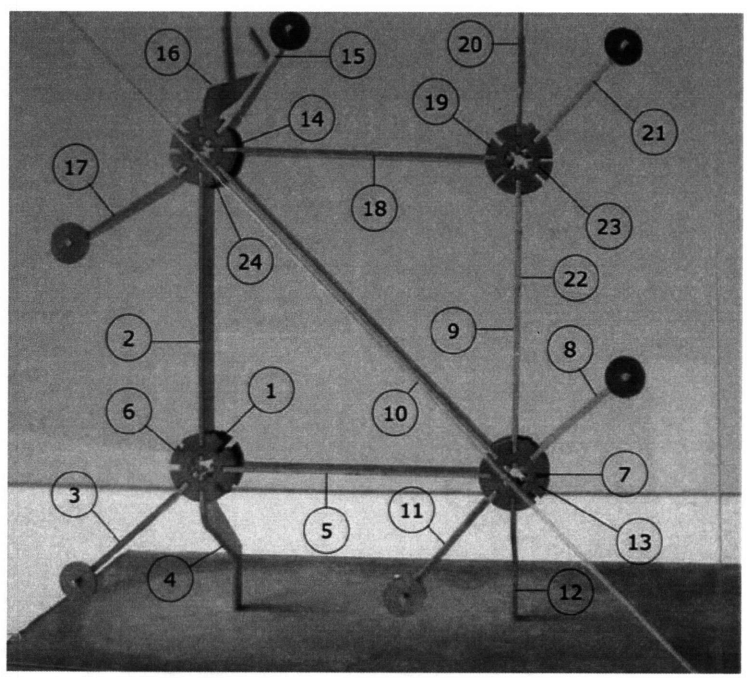


Fig. 7-4. The assembled façade panel

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[6] **Individual project in class *4.592 Special Problems in Digital Fabrication* (Prof Lawrence Sass), Massachusetts Institute of Technology, Spring 2007. Dimitris Papanikolaou.**

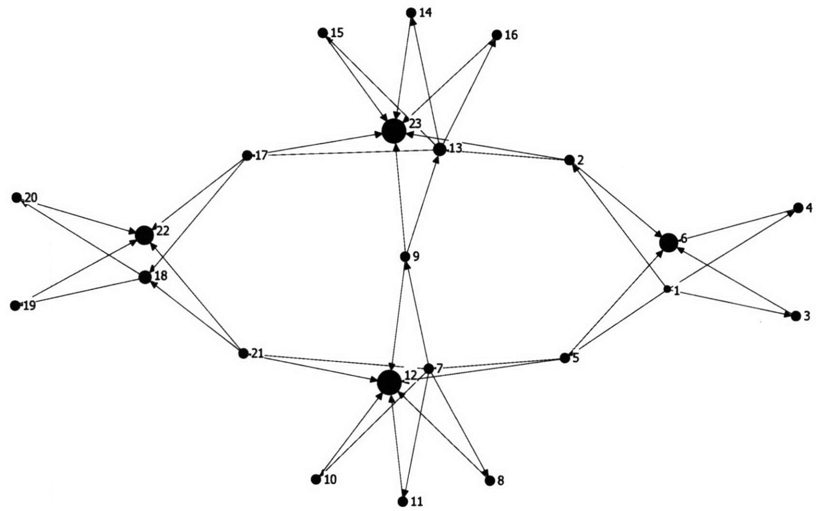


Fig. 7-5. Liaison graph of the panel with size of node proportional to in-degree

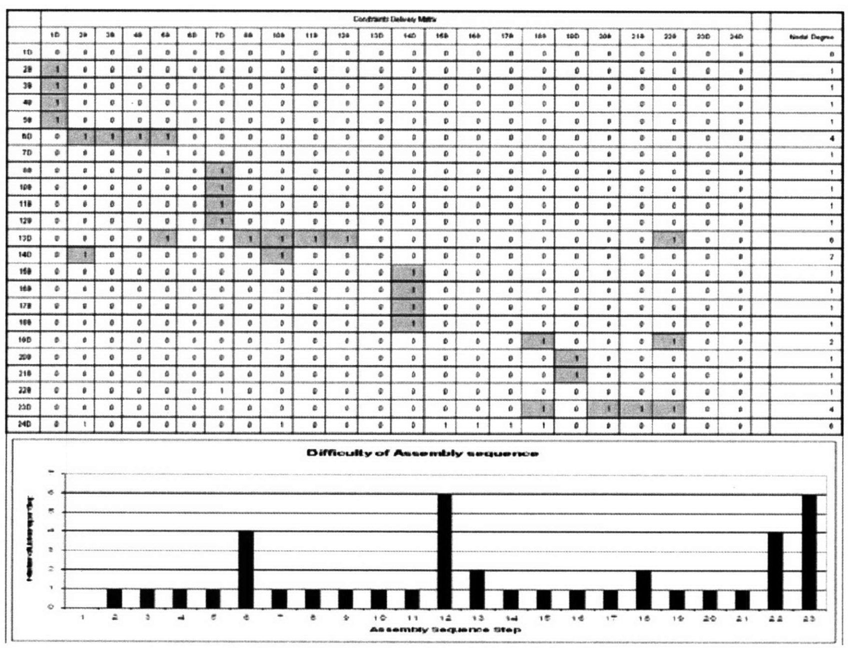


Fig. 7-6. Assembly sequence matrix, degree distribution

A representation of the assembly with the liaison graph shows that while the assembly is possible, there are two steps in the assembly sequence of high difficulty because they need simultaneous connections. The nodal degree distribution along the actual assembly sequence shows the difficulty of each step as a function of the number of connections that have to be achieved with the rest of the assembled artifact. The nodal degree sequence is then inserted as input in the simple System Dynamics model that represents the assembling process. The model clearly shows that assembling rate will significantly drop at the 12th and 23rd step of the assembly sequence.

7.2.5.1 Explanation of the System Dynamics model

The stock and flow structure of the System Dynamics model consists of two stocks, the *Parts to be Assembled* and the "Assembled Parts". Parts move from one stock to the other through the *Assembling Rate*; the faster the *Assembling Rate*, the less time will take for the assembly to be completed. However, due to errors some parts will need to be disassembled and reassembled. Therefore there is a *Disassembling Rate* that removes parts from the *Assembled Parts* stock back to the *Parts to be Assembled* stock.

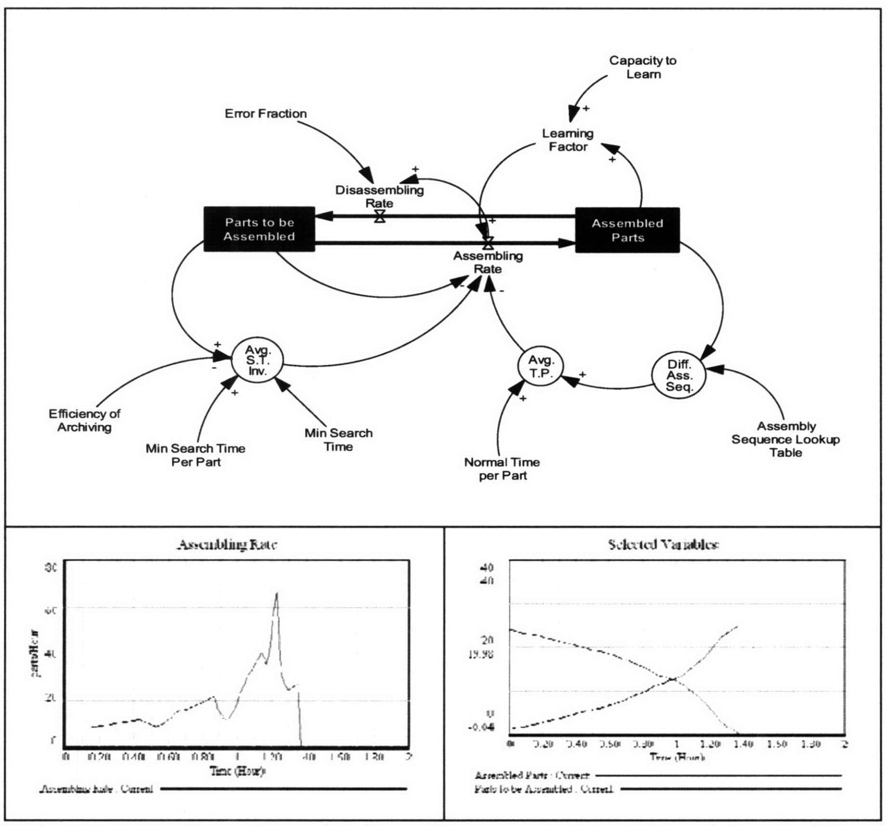


Fig. 7-7: System Dynamics model of assembly process and simulations of the assembling rate and the two stocks

The *Assembling Rate* depends on the following factors: first, the *Learning Factor* and the *Capacity to Learn;* the more we assemble the more skillful we get which improves our assembling rate. Second, the *Average Search Time in Inventory (Avg.S.T.Inv);* average search time depends on *Efficiency of Archiving,* which is how well organized the parts are in the inventory. Third, on the difficulty of the assembly sequence that is given by the *Assembly Sequence Lookup Table.* The lookup table returns the in-degree of each step of the assembly sequence. The *Disassembling Rate* depends on the *Error Factor* and on the *Assembling Rate.*

This System Dynamics model is rather unnecessary for such a small assembly as the Façade Panel of the example; however it clearly shows that in combination with the liaison graph it provides a powerful tool for evaluating difficulty of a more complex assembly project. With this approach we can identify points in the process where we would expect the production rate to drop and accordingly plan our construction schedule. Another benefit of this approach is the high level of abstraction.

8 THE VALUE CHAIN

Combining Structure and Dynamics

8.1 Chapter overview

Chapter 8 deals with the value chain. It integrates chapters 6 and 7 to build up the structure of the value chain and use it to simulate a system dynamics model of the project's performance. Moreover, it present how design dependency might cause conflicts in the value chain if it is different that the assembly dependency. Finally, it present some thoughts and ways of how this technique can be used to map and evaluate the entire value chain of an artifact. Chapter 9 ends with an example of a value chain.

8.2 Unraveling the value chain

Purpose of a value chain for planar part assemblies is to fabricate, deliver and assemble an artifact of custom parts according to the liaison graph. Therefore the liaison graph provides the backbone, and the assembly sequence provides the order of the tasks that have to be executed by the value chain so that all resources and parts arrive at the right time for their turn in the sequence. Because of that, the liaison graph constitutes the starting point of the analysis. Starting reversely, from the liaison graph, we can first add assembling processes, then the distribution processes, then the fabrication processes, and finally the design attributes and decision functions. If we get the attributes graph from the bipartite graph of the APM model of the value chain then we get the structure of the supply chain.

8.2.1 The supply chain

The supply chain consists of the different states of each attribute, without the value adding processes. For example, a supply chain of an assembly of three parts will include the final states of the parts' attributes (liaison graph); the previous states of these parts before they were assembled (the construction site inventory states); the states of the parts after their fabrication (fabrication inventory); and finally the states of the parts before fabrication at the various raw resource suppliers (table 9-2-3)

8.3 *From APM to System Dynamics*

Every digital fabrication project can be modeled as a combination of design, fabrication, distribution, and assembly rates in System Dynamics. However, the question is first how to build the stock & flow structure and second, how to control the rates. To augment the feasibility analysis of a digital fabrication project I propose a 3-step process: first, map the value chain in APM starting from the liaison graph; second analyze the value chain for structural inconsistencies using network analysis methods; third, collapse the branches of the value chain to get the basic structure of a System Dynamics model. Then, the System Dynamics model can be further refined.

8.3.1 *Step 1: Construction of the Value chain Network*

Starting from the liaison graph the entire value chain network can be constructed. Consider the liaison graph of the three parts of the example in the previous section. The next step of the process is to add the assembling processes, the decision functions, and the previous states of the parts before they are assembled. Each part attribute represents the in-degree of that part. Next, we add the fabrication processes and the attributes of each part before and after fabrication. During fabrication, fabrication processes use resources to produce the parts. Finally we add the design attributes that control fabrication and assembly processes.

8.3.2 *Step 2: Structural Analysis of the value chain network*

Once a complete network of the value chain exists we can use this model to identify structural inconsistencies and predict points of risk using network analysis. The robustness analysis consists of tracing the loops that the system will follow in correcting an error. Typically such a loop would be to reassemble, refabricate, or redesign a part of the design.

From the complete value chain network there are several sub-networks that can be extracted. These are the design attributes network (The CAD graph), the supply chain network, the task network. Each of these networks is suitable for application of network analysis routines to locate nodes of high risk.

Several concepts useful for identifying points of risk in a task network using network analysis are presented in Appendix C.

8.3.3 Step 3: Collapsing the network into clusters to build a System Dynamics model

From the complete value chain network we can start collapsing all common attributes and all common processes to clusters by the following rule: two nodes of the same type can be collapsed into one if they both connect to a node of a different type.

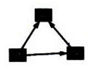
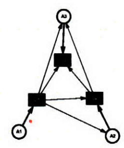
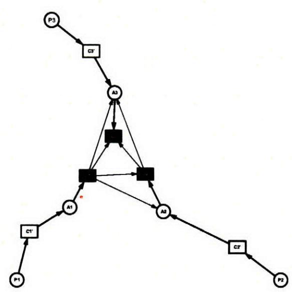
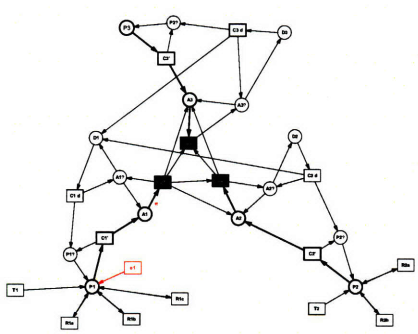
	1. Liaison graph of 3 parts
	2. Assembly processes constrain each part by using the previous in the assembly sequence
	3. Fabrication processes added. Each fabrication process creates a part that will be used by the corresponding assembly process
	4. Decision functions added. Design attributes that control decision functions added. Design processes that modify design attributes added. Resource attributes and tool attributes added. Design dependency structure different than assembly dependency structure.

Table 8-1: Mapping of value chain from a 3- part liaison graph

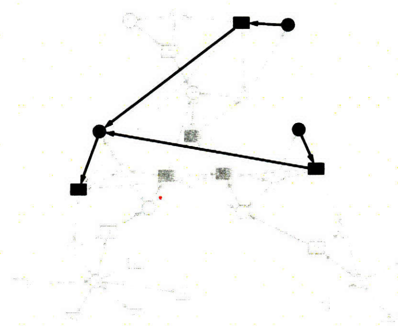
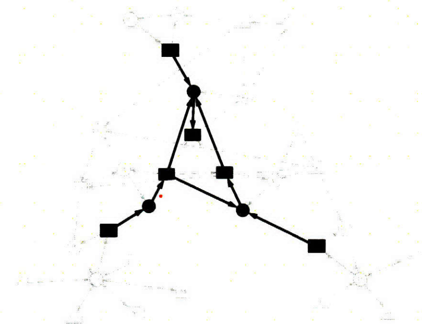
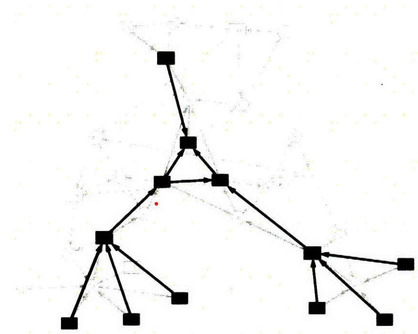
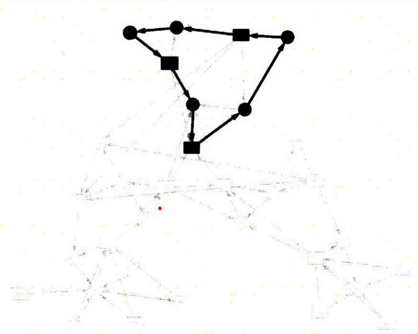
	1. Design Dependencies (CAD)
	2. Assembly processes with the 3 parts before and after their constraint.
	3. Supply chain network (artificial attributes only)
	4. Error correcting loop: A response to an error in assembly of part 3, makes decision function to call design process and then fabrication process to refabricate a new part and send it back to the construction site.

Table 8-2: Analysis of a mapped value chain from a 3-part liaison graph

PART III - CONCLUSION

Structure of part III

Part III is organized into two chapters: chapters 9, and 10.

- **Chapter 9 presents the results of the work and experiments.**
- **Chapter 10 presents the conclusion and some thoughts and suggestions for future research.**

9 RESULTS

9.1 *Chapter overview*

Chapter 9 presents the results of the work and experiments.

9.2 *Results*

Application of network analysis methods to evaluate assemblability of a design is a significant help during design process. The analysis can start before the final CAD model is finished since the liaison representation uses the normal vectors. In the experiments the presented method was successful in revealing information that cannot otherwise be studied with typical digital modeling techniques. This thesis showed that we can use metrics from a network model such as the liaison graph to include them in a System Dynamics model. Points in the process of high difficulty were located and they would be valuable if the designers followed this methodology during design. Modeling of a value chain for a construction project can be a tedious work. This partly because of the effort needed to convert the information into attributes and processes. The entire proposed workflow is the one presented in fig. 9-1.

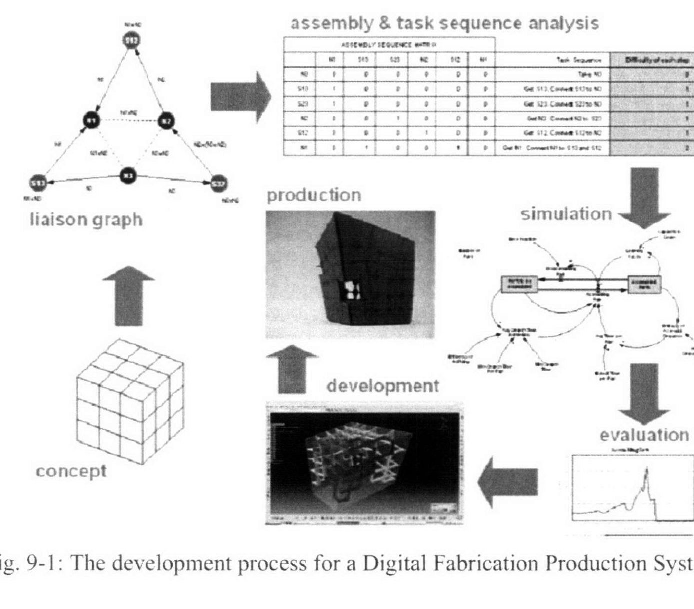


Fig. 9-1: The development process for a Digital Fabrication Production System

10 DISCUSSION

10.1 Chapter overview

Chapter 10 presents the conclusion and some thoughts and suggestions for future research.

10.2 Conclusion

This thesis attempted to reveal, describe, and formulate a problem in the field of digital fabrication that to my mind and experience is important. This problem deals with the lack of tools and theories from architects to control and evaluate production of assemblies. Moreover, this thesis explored other disciplines that address similar problems and tried to bring together concepts and tools from these disciplines to address the problem. Finally, this thesis provided some possible directions for addressing this problem.

10.3 Future research

As this thesis closes it gets clearer to my mind that digital fabrication in architecture lacks of formal tools in two main areas: *assemblability assessment*, and *production flow management*. But it is the concept of digital fabrication such, that unless these problems are firmly addressed a DFPS will remain in the sphere of imagination. This thesis suggests that if architecture wants to employ digital production means and methods to mass customize buildings, then architects should embrace tools, methods, and theories from the fields that has been already dealing with these directions: the fields of product development and industrial management. I suggest the following possible fields of future research in digital fabrication that should go in parallel with existing research in CAD/CAM:

- Embedding of information from databases from CAD solid models into System Dynamics models to evaluate production rate.

- *Theory of assemblies for architectural production.* As computational generative design strategies become a popular field of research in Digital Fabrication so does the need to understand assemblies as systems; the question is not how to decompose a solid form into components, but how these components interrelate both structurally and functionally. Issues such as modularity or integrality of an assembly are essential for *guiding* our computational tools.

- *Structural Description and management methods for modular systems with multiple levels of interaction between their modules.* Consider for example a decomposable small house into prefabricated components. Assembly architecture is one issue; however, another issue is the electrical network, the plumping network, and other service networks. Each of these networks serves a purpose but it often conflicts with the other systems. This is because each of these systems operates on the same platform but with different requirements. Therefore, a firm research into the field of digital fabrication for mass customization needs soon to employ research in these fields. The Design Structure Matrix and other network analysis methods have been extensively applied to address these problems in other disciplines.

- *Mapping and dynamic simulation of value chains.* Value chains should be addressed as living organisms. First, definition of properties which have to be mapped. Second, definition of proper description and modeling tools. Third, definition of behaviors of the properties which have to be diagnosed. Finally, definition of computational methods to dynamically simulate and monitor these behaviors. As an example, what are the mechanisms and feedback loops that are involved in a value chain that recovers from an error in the construction site?

- *Theory of decentralized production systems for mass customization.* What is a production system and how can a decentralized network based system work? What parameters define robustness of such a system? To my mind, defining robustness, the ability to recover from errors, is far more important than defining perfection in a production system.

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12 LIST OF FIGURES

All figures are property of the author except:

Figure 3-9: *The liaison graph of a V8 Engine* on page 28. This image was generated by the author based on material derived from Prof Daniel E. Whitney.

Figure 3-10-: *A System Dynamics model of a supply chain and simulations,* on page 29. This image is based on material from course 15.874 System Dynamics.

APPENDICES

Appendix A

12.1.1 Assembly Analysis of a Parametric Box

The following experiment refers to the design, fabrication and assembly of a box made from interlocking planar parts. The challenge of the project was to find a generic parametric solution for the configuration of the structural frame so that the planes of the ribs of the frame and the panels of the skin of the box remain perpendicular for any instance of the input variables. The input variables of the problem where:

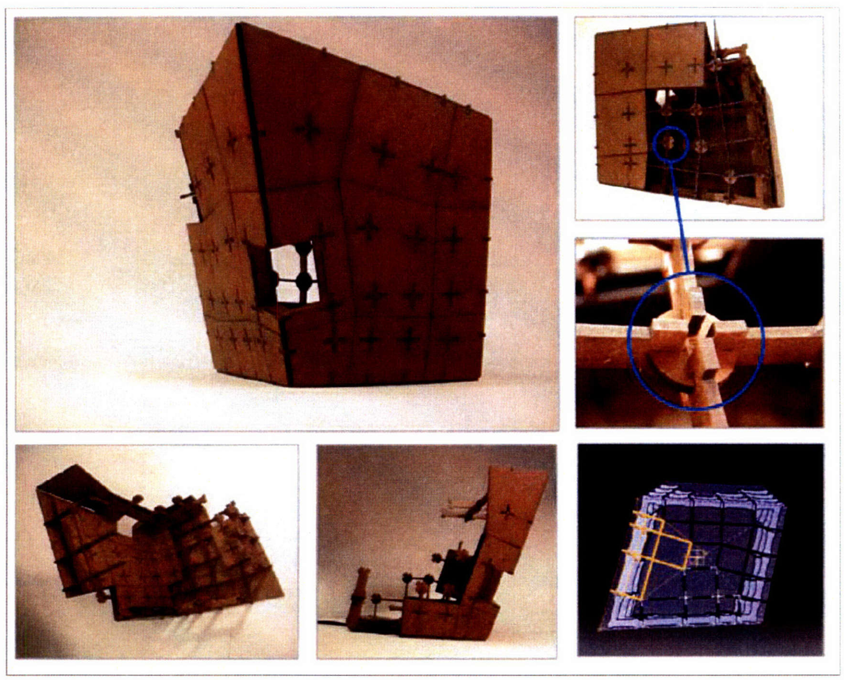
- The 6 pairs of angles that determined the directions of the normal vectors of each of the six faces of the box
- The thickness of the planar material
- The density of the structural grid and accordingly the density of the panels of the skin

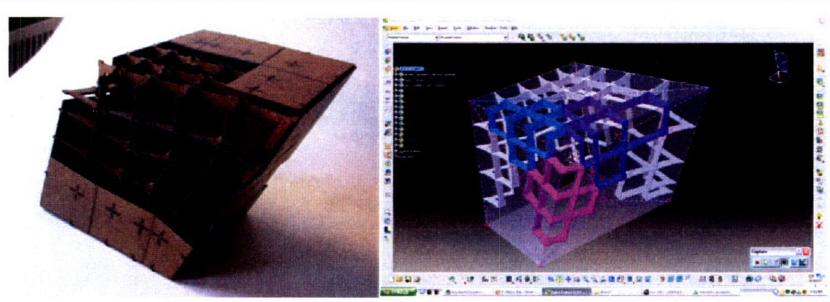
The parametrically associated parts ought to automatically update if any of the input variables changed. The box was designed in 3D CAD modeling software (CATIA) and the parts were fabricated from 1/8" Masonite sheets in a laser-cutter.

The parametric geometric solution was successful. Indeed the algorithm provided a solution for the orientation and configuration of the grid for any input variable. The solution consisted of 12 subassemblies of 8 parts each (fig. A-1). The total number of parts was 252. They were organized as follows: 8 subassemblies of 12 part each; 48 disks that connected the subassemblies in pairs of 2; 108 panels for the skin of which 54 were in the exterior and 54 were in the interior of the box

However, it soon became obvious that the difficulty of the problem was not only the parametric geometric solution of the planes of the parts; the management and analysis of the assembling process of during assembling process was particularly challenging. It became obvious that installation of some parts (the disks) was impossible without warping the flat material. At the time when the project took place there were no formal tools to analyze assemblability of the solution. Therefore these problems were faced during assembly, after the fabrication of the 252 parts.

The following analysis of the assembling process using the liaison graph reveals the problem.





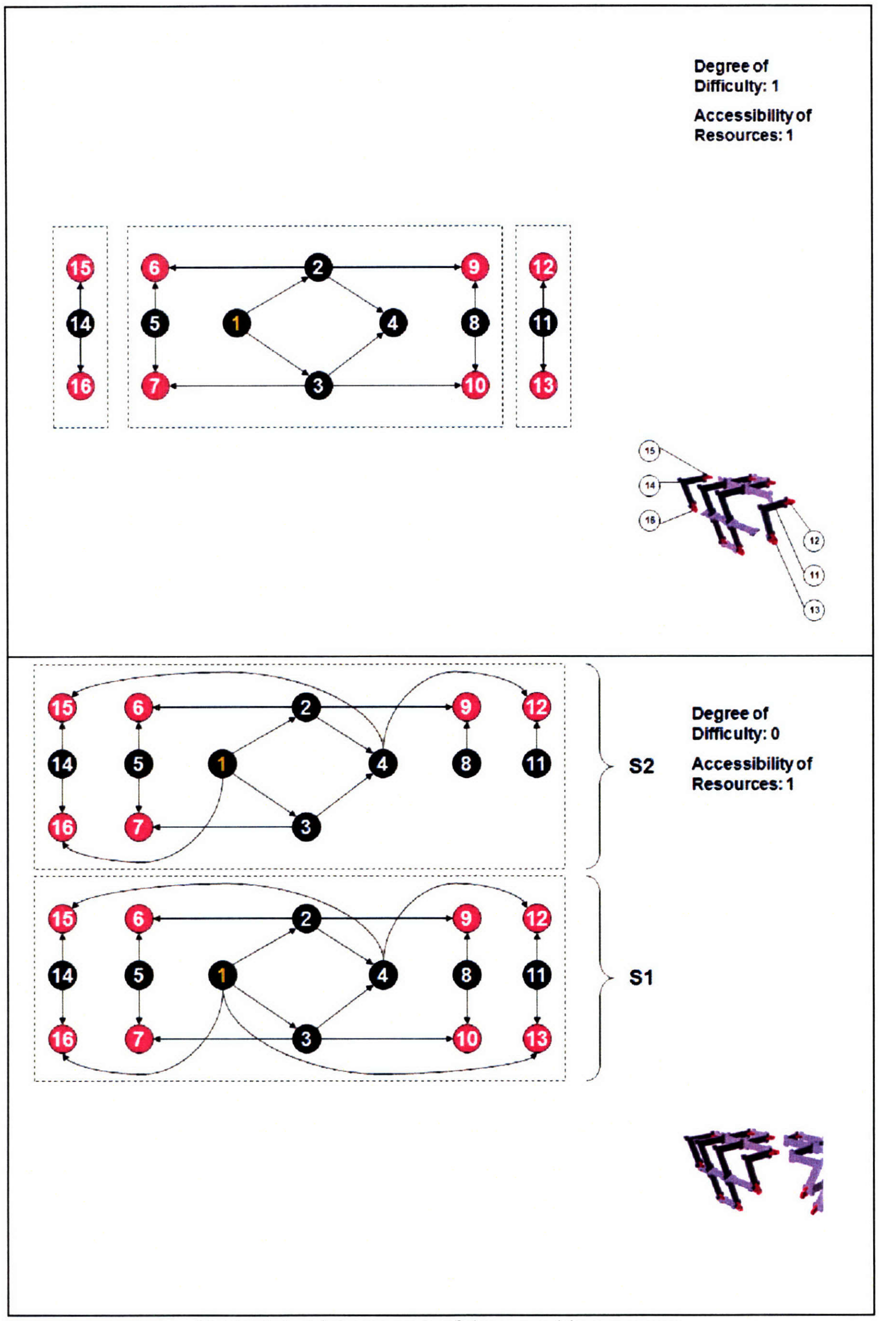


Table A-1: Liaison graph of the assembly sequence.

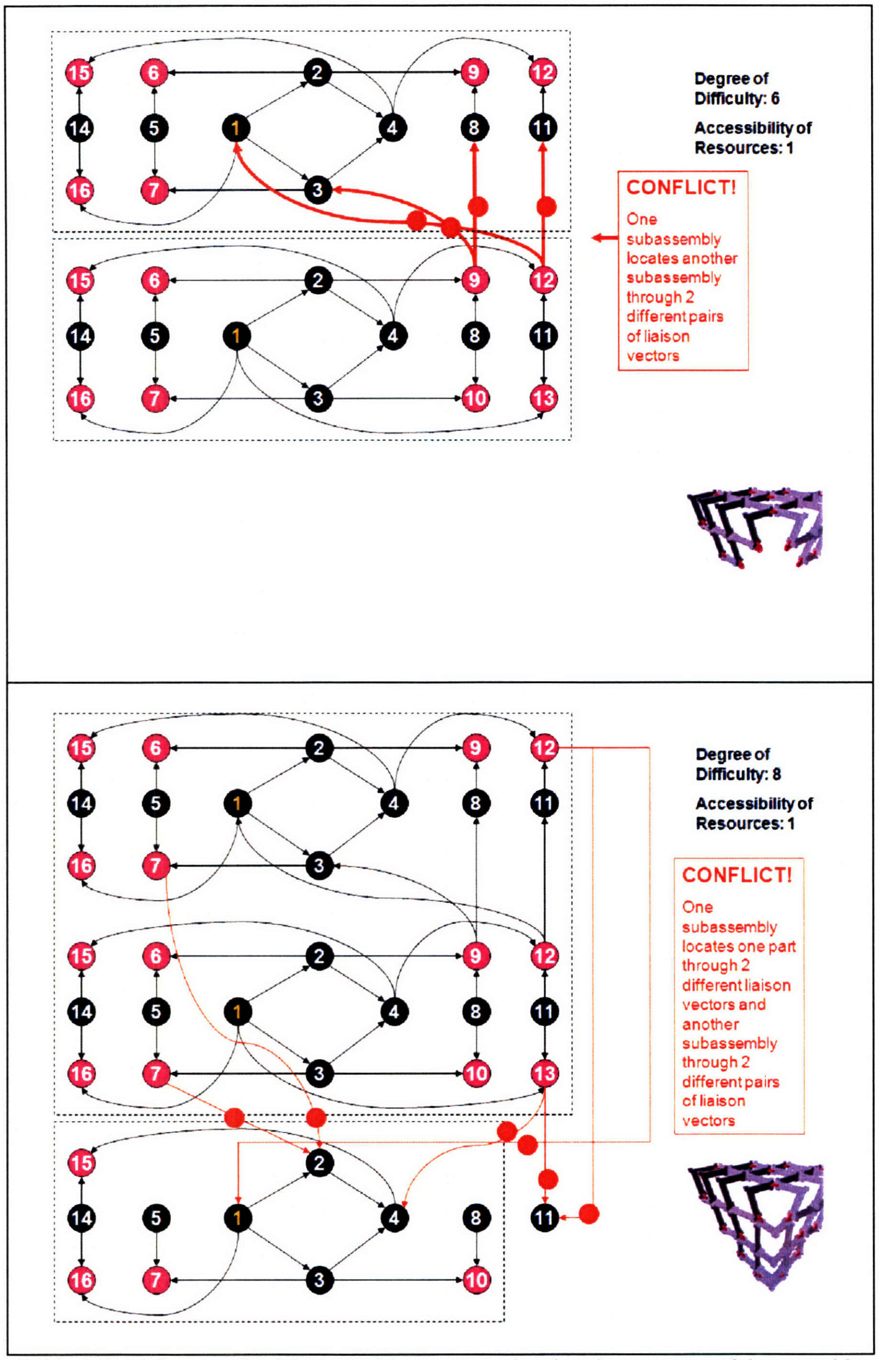


Table A-2: Liaison graph of the assembly sequence showing the two steps of the assembly with the problems.

Appendix B

12.1.2 Conversion of a System Dynamics model of a supply chain to a Design Structure Matrix and a network model

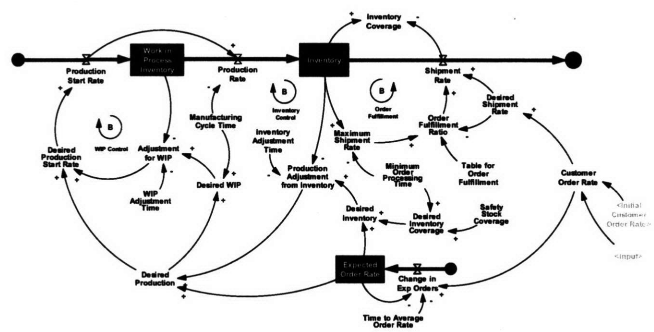


Fig B-1: The System Dynamics model of the supply chain

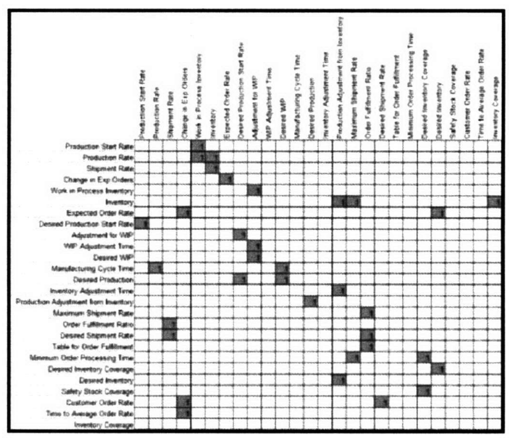


Fig. B-3: The System Dynamics model can be converted to a Design Structure Matrix

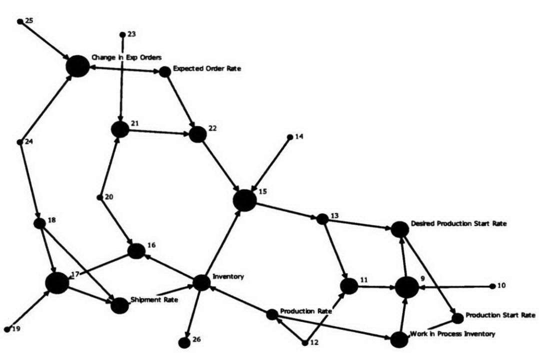


Fig. B-4: The corresponding Network model of the System Dynamics model

Appendix C

12.1.3 Network Analysis of a Construction Schedule

Assuming the following:

1. Every task has a random error probability *e* to its descendent task and a random correction factor *c* to the error of its precedent task and that errors start at nodes with high in-degree.
2. Errors propagate and build up in long chains.
3. Errors are solved in communities (high connectivity of tasks might imply that a task can correct its neighbors)

Then:

1. The more distant and the higher in-degree has a random node from the end node the more risky the project is
2. If nodes with high in-degree connect to nodes of high out degree then errors propagate
3. In a task network the in-degree can inform on how difficult a task is (requires simultaneous resource from many precedent tasks), while the out-degree can inform on how important a task is (many other tasks depend on its successful completion.

- Can we evaluate risk of project by locating risky tasks and measuring their distance from the end?
- Metrics of interest:
  - In-Degree distribution along task sequence (difficulty along schedule)
  - Out-Degree distribution along task sequence (importance along schedule)
  - Nodes with high in-degree, out-degree
  - Communities
  - Nodes that connect to nodes with high in-degree, out degree
  - Distance of risky nodes from start and end of project
- Another network that is of particular importance is the network of the artificial attributes; that is the network of the parts, materials and resources in the value chain. In other words the supply chain of the project.

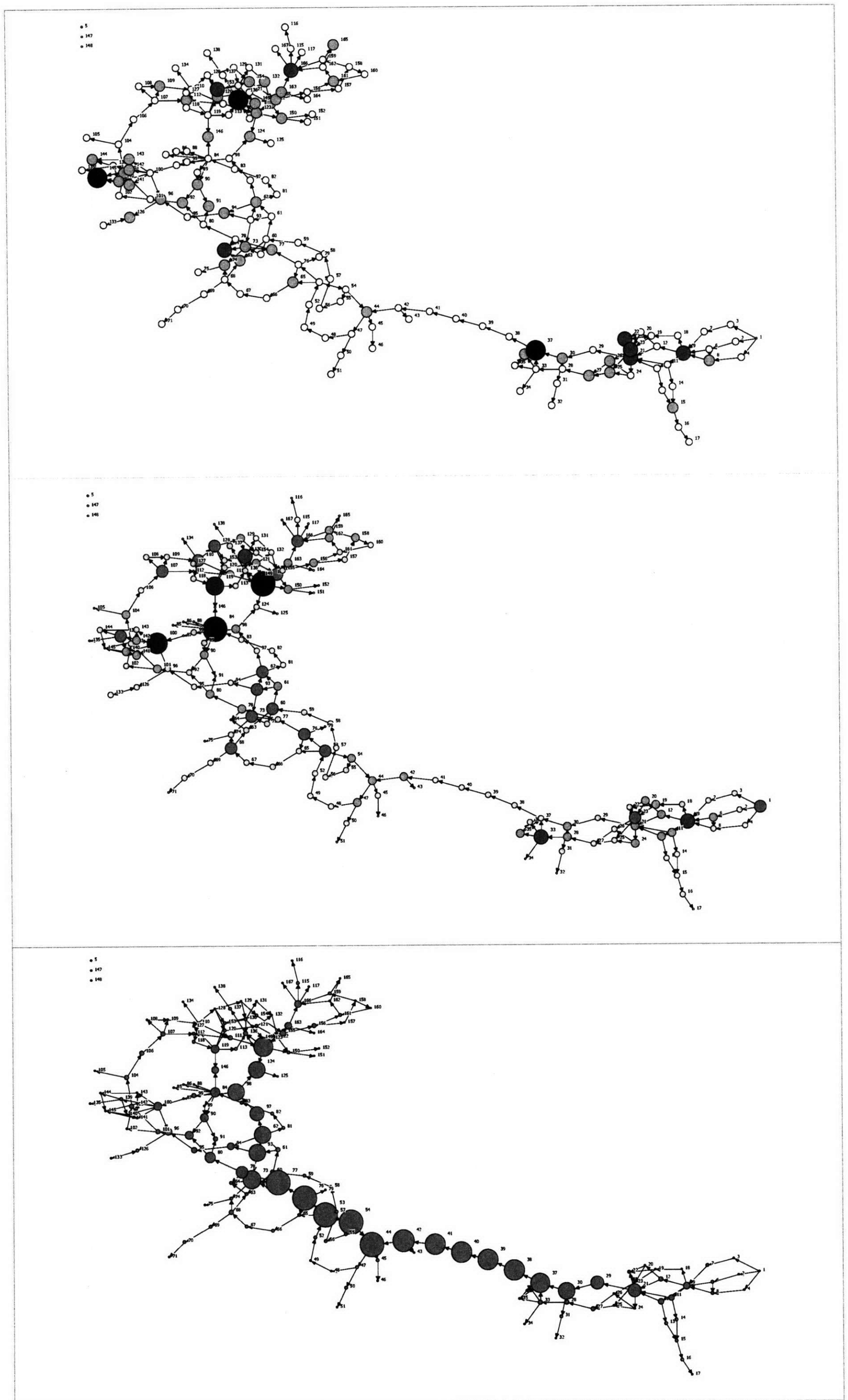


Fig. C-1: Task sequence network of a concstruction schedule. Top: node size proportional to in-degree (difficulty). Middle: node size proportional to out-degree (importance). Bottom: node size propotional to "betweeness" value.

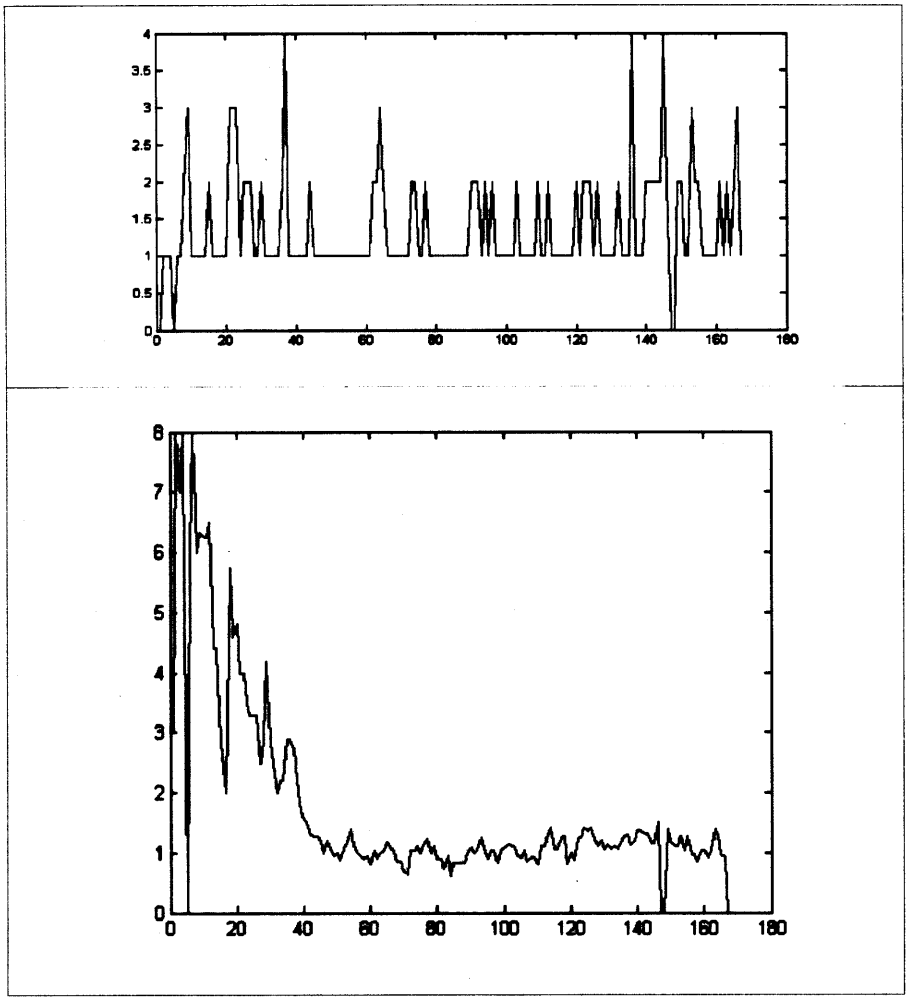


Fig. C-2: Top: in-degree distribution of nodes along task sequence. This graph denotes difficulty of the process. Bottom:cumulative neighbor degree divided by distance from start of project. Indicates how far from the start of the projects risky tasks are.

Appendix D

12.1.4 From liaison graph to a System Dynamics model

This example shows an assembly of four parts. The assembling processes with the decision functions are added to the liaison grap to build an APM model of the value chain (in this example only the assembling processes). The design description that informs the decision functions is the nodal degree distribution of the assembly sequence (the list 0,1,1,2).

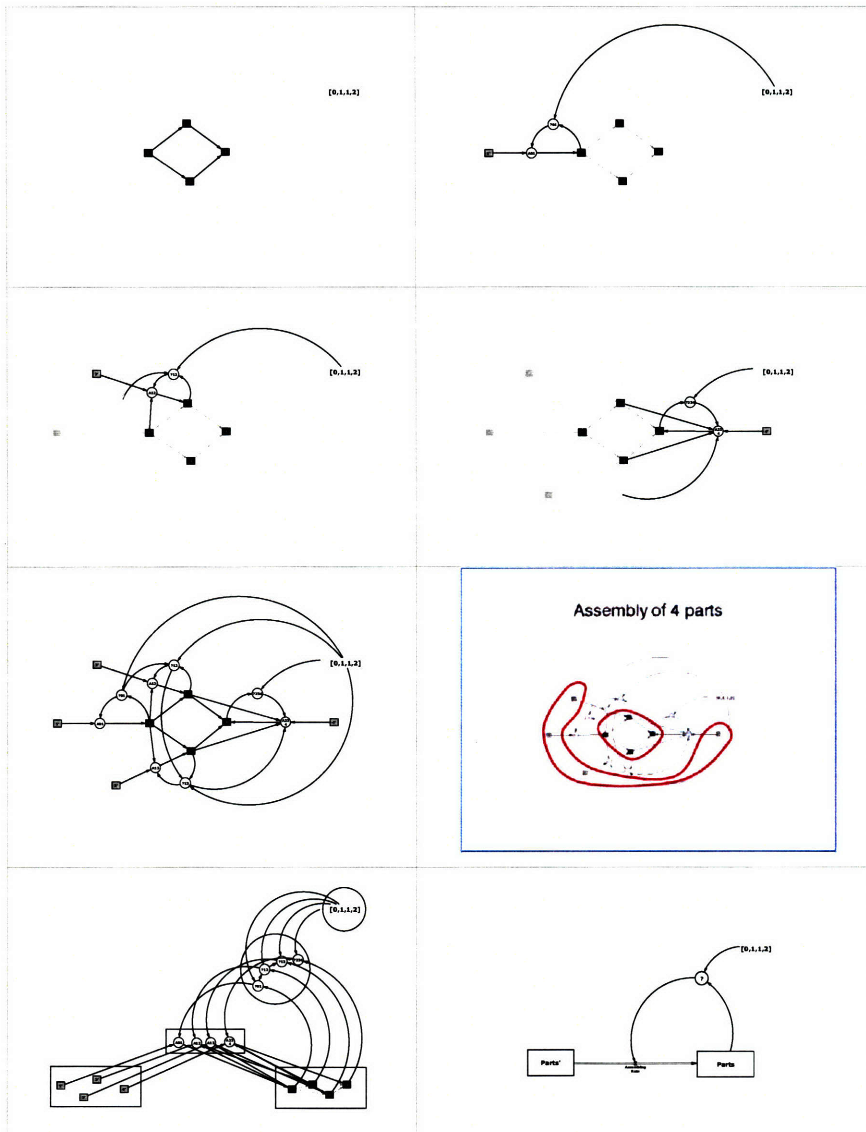


Fig. D-1: APM model of assembly sequence of 4 parts and collapsing to a System Dynamics model.

Appendix E

12.1.5 Basic behavior patterns of a production system in APM