Building Competencies in Sensor Harness Manufacturing through Prototyping

by

Stacy Bergman

Bachelor of Science in Electrical Engineering, Oklahoma State University, 1995

Submitted to the Department of Electrical Engineering and Computer Science and the Sloan School of Management in partial fulfillment of the requirements for the degrees of

Master of Science in Electrical Engineering
and
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In conjunction with the Leaders For Manufacturing program at the
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Abstract

Organizational knowledge is information about products, processes and customers that is held by the personnel in the organization. Institutionalization of the best practices contained within this knowledge is essential in creating competencies. Unfortunately, organizations do not utilize this knowledge effectively. This thesis introduces a framework that shows how establishing a prototype system to enhance product and process understanding can start to build organizational knowledge in the short-term. Along with external benchmarking, this internal knowledge can be used to form best practices based competencies. This framework will be illustrated through the use of a case study.

The case study was conducted at the Delphi Automotive Systems Mexico Technical Center. The case study project was undertaken to improve the Energy and Chassis Systems division's competencies in sensor wire harness products. In order to support this competency development, the author worked with Delphi Automotive Systems personnel to develop best practices based competencies employing the competency development framework introduced in this thesis.

Installation of a working prototyping system was achieved in the six-month project period. Through the production and delivery of these harnesses, internal best practices were developed. These were used along with benchmarking of other harness manufacturers to develop a baseline best practices based competencies repository for the division.

Effective use of the best practices based competencies developed during the case study project should foster improvement in competitive metrics, particularly speed-to-market and product development costs. Extension of best practices based competencies development to other products will allow human and monetary capital to be released from re-engineering tasks. These resources can then be refocused on product advancement to exceed customer expectations in the automotive market. It will also allow the organization to focus resources on development of strategic non-automotive markets in order to diversify the business to protect against future downturn in the automotive market.

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Al Webster – Chief Manufacturing Engineering
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Dedication

The author wishes to dedicate this work to the memory of Dr. Leonard Stone. He was a sensible businessman, practical engineer and loving grandfather. He is deeply missed.

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Biographical Note

The author, Stacy Bergman, is a Leaders For Manufacturing Fellow at Massachusetts Institute of Technology. Her fellowship is sponsored by Delphi Automotive Systems. Ms. Bergman is a June 2001 candidate for dual Master of Science degrees in Electrical Engineering and Management. Her previous education is a Bachelor of Science in Electrical Engineering from Oklahoma State University in December 1995.

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Chapter 1

Strategic Knowledge and Competency Management

1.1 Organizational Knowledge

Organizational knowledge is the information that personnel possess about products, processes and customers. This knowledge is rooted in the experiences, successes, failures, contexts and interpretations of the personnel within the organization. Regardless of size, product, industry or location, every organization contains a quantity of this valuable knowledge.[1]

Unfortunately, organizations often are not aware of the vastness or the value of the knowledge that is resident in a subset of the personnel.[2] This lack of awareness, and subsequent limited utilization, is often due to the nature of the knowledge. When the knowledge is inferred, it is often difficult to articulate for use across the organization. However, even when the knowledge can be captured in a format that makes it usable, organizations often fail to exploit their knowledge assets.

1.2 Knowledge Management

Knowledge management enables control of the organization's informational assets. Effectively institutionalizing the best practices contained within the knowledge is an important step in creating organizational competencies.[3] At the center of knowledge management is the systematic creation, detection, collection, perception, adaptation, distribution and utilization of information.

Knowledge is developed through interactions with internal sources. These sources include the documentation that is utilized and the communications that are made in day to day business. Knowledge is also developed through interactions with external sources. External knowledge can be gained through processes such as benchmarking, competitive intelligence and reverse engineering. It can also be gained through information sharing with the customers and suppliers of an organization.

At the source of the internal and external knowledge are individuals. Individuals create the knowledge. Knowledge developing organizations give each individual the vision based context with which to frame knowledge development, the personal flexibility with which to build mental models and the organizational flux with which to motivate new knowledge. These organizations also establish systems that allow for experimentation to prove new knowledge concepts with clear criteria for knowledge verification.

There are two forms of knowledge within individuals. These types are codifiable and tacit. Codifiable knowledge can be articulated. However, for an individual, codifiable knowledge is

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[1] Grayson, Randall. "Excuse me, isn't that your library on fire?" Camping Magazine. September/October 1998. <http://www.findarticles.com/cf_0/m1249/n5_v71/21186894/print.jhtml>.
[2] Davenport, Thomas H, David W. DeLong and Micheal C. Beers. "Successful knowledge management projects." Sloan Management Review. 39.2 (Winter 1998): 55-58.
[3] McEvily, Susan K., Shoba Das and Kevin McCabe. "Avoiding Competence Substitution Through Knowledge Sharing." Academy of Management Review. 43.2 (April 2000). <http://www.findarticles.com/cf_0/m4025/2_25/62197041/print.jhtml>.

interconnected with the tacit knowledge that is routed in personal mental models. In order to manage this knowledge so that all the individuals within the organization can utilize it, systems for sharing mental models and basic knowledge must be utilized.

Individual knowledge can become organizational knowledge through knowledge sharing and transferring. The most valuable knowledge shared will gain momentum that will allow it to be institutionalized as an organizational competency. However, knowledge sharing across an organization is not simple. Systems to share knowledge must include means of making four types of knowledge transfers. These transfers are tacit knowledge to tacit knowledge, codifiable knowledge to codifiable knowledge, tacit knowledge to codifiable knowledge and codifiable knowledge to tacit knowledge.

Transfer of tacit knowledge to tacit knowledge is accomplished through socialization. Socialization is verbally and physically sharing similar experiences. Transfer of codifiable knowledge to codifiable knowledge is completed through combination. Combination is assembling the articulated knowledge into a centralized and usable framework such as a repository. Transfer of tacit knowledge to codifiable knowledge is done through externalization. Externalization is sharing personal metal models through the use of metaphors and analogies so that others can make mental model comparisons. Transfer of codifiable knowledge to tacit knowledge is fulfilled through internalization. Internalization is simply individual learning. Organizations that possess systems that facilitate socialization, combination, externalization and internalization are able to institutionalize individuals' knowledge into organizational knowledge.[4]

Knowledge management does not end at institutionalization. Knowledge creation and institutionalization is a never-ending process. In order to facilitate knowledge utilization, continued dedication of resources is required to assure that the information is in assessable formats. These resources are also required to enable continuous improvement to guarantee that the knowledge of the organization reflects the best information available.

1.3 Best Practices Repositories Rationale

There is a tremendous amount of knowledge within organizations that is not applied in product or production process design. Since the personnel who should be utilizing the knowledge are not aware that it exists, exploitation of the knowledge does not occur. Centralized best practices repositories are created to methodically maintain the knowledge in order to solve this problem. These repositories attempt to increase knowledge exploitation by providing accessible information for the entire organization.

Best practices repositories provide additional benefits. An organization's knowledge is centrally captured instead of residing with specific personnel who can leave the organization at any time. Providing accessibility to the organization's knowledge forces decisions to be less dependent on the responsible individual's depth of experience. Instead, the collective knowledge of the entire organization is utilized to make decisions. There is less dependence on costly repetitive creation of physical samples and more dependence on cost-effective centralized information. The best practices repositories provide a framework for product and production processes standardization

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[4] Nonaka, Ikujiro. "A Dynamic Theory of Organizational knowledge Creation." Organization Science. 5.1 (February 1994): 19.

when appropriate. Similarly, the repositories standardize the channel to communicate organizational knowledge.

Properly managed best practices repositories are comprehensive representations of organizational competencies. When guarded internally and used strategically, the knowledge within these repositories can offer an organization a competitive advantage.[5] The best practices can be utilized to simplify design, source and manufacture decisions. The goal of this simplification is to release human and monetary capital from re-engineering tasks. Then, these resources can be utilized on product advancement to exceed customer expectations and to improve the bottom line. Continuous repetition of this cycle enables an organization to consistently beat the competition to market in supplying products the customer wants at a superior price structure.

1.4 Thesis Organization

This thesis introduces a framework that shows how establishing a prototype system to enhance product and process understanding can start to build organizational knowledge in the short-term. Along with external benchmarking, this internal knowledge can be used to form best practices based competencies. This framework will be illustrated through the use of a case study.

Chapter 1 has introduced the general organizational environment that serves as a rationale for knowledge management to improve the competitive position of an organization in the market.

Chapter 2 discusses best practices based competencies. The rationale for developing competencies and general development frameworks is introduced. The chapter details the preferred components of a competency development framework.

Chapter 3 introduces the proposed competency development framework. This framework incorporates internal knowledge institutionalization and external knowledge detection. This framework also includes experimenting or producing as a practice to enhance product and process understanding. The ultimate goal of the framework is to form best practices based competencies that can allow an organization to gain competitive advantage.

Chapter 4 provides an introduction to the case study project. It includes basic information pertaining to the business background, the project requirements and the project plan. Included in this chapter is a section on the rationale for choosing a specific product family as the project focus. This chapter concludes with details pertaining to the product family.

Chapter 5 presents the case study project utilization of the proposed competency development framework. The chapter details the four steps of the development framework utilizing project specifics. The chapter discusses a baseline set of product and process requirements, a prototyping system and a benchmarking study. The chapter concludes with a discussion of the best practices developed through employing the competency development framework.

Chapter 6 details the results and conclusions based on the work completed during the project period. It closes with recommendations for further competency development framework extensions through an integrative best practices strategy.

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[5] Lado, Augustine A. and M. Zhang. "Expert Systems, Knowledge Development and Utilization, and Sustained Competitive Advantage: A Resource-Based Model." Journal of Management. 24.4 (July/August 1998): 489-509.

Four case study project appendices complete the thesis. In Appendix A, specifics of the case study project prototyping system are detailed. Appendix B describes the case study benchmarking efforts and presents the conclusions of the information collected through the study. In Appendix C, process best practices developed during the case study project are presented. Appendix D details several potential design best practices developed during the case study project.

1.5 Chapter Summary

This chapter has developed the rationale for developing best practices repositories as organizational knowledge centers. The need to manage organizational knowledge due to its potential competitive advantage was presented. Utilization of the knowledge included in best practices repositories to gain speed-to-market and cost structure competitive advantages was detailed. This chapter concluded with an explanation of the organization of the remainder of the thesis.

Best Practices Based Competencies

2.1 Competencies Development Rationale

When guarded internally and used strategically, best practices based competencies can offer an organization a competitive advantage. However, developing competencies in every realm of an organization can be cost prohibitive. Similarly, improper management of best practices and organizational competencies can create a competitive disadvantage.

In order to avoid the negative cost structure associated with creating competencies in all functional areas, each organization must determine where there are potential synergies. Best practices based competencies should be developed that enable exploitation of these synergies. When competencies are developed across multiple product lines, development costs can be counterbalanced by product volume.

Best practices based competencies that are developed to mirror product synergies should be utilized to make business decisions in order to provide profitable value to customers.[6] In the areas of the organization where there are limited synergies, suppliers in the market should be engaged to create competencies. Developing the competencies that provide a competitive advantage internally while taking advantage of the best practices of suppliers in other domains will allow an organization to maintain a competitive advantage in products delivered and cost structure.[7]

Ineffective knowledge management can cause potential organizational competencies to become a competitive disadvantage. If the best practices repository is inflexible or inaccessible the contents will not be utilized to gain a competitive advantage. Similarly, if the repository is not amendable, the competencies contained within will only be a competitive advantage for a moment in time. Organizations must continue to acquire new competencies from internal and external knowledge sources to meet the changing market needs and to remain competitive in an industry. In the extreme, a best practices repository that is not continuously improved contains outdated competencies that can become competitive disadvantages.[8]

Even with proficient utilization of supplier competencies and competent management of organizational knowledge, there is another potential risk in the development of competencies. This risk is the introduction of disruptive[9] technologies into the market. When new technologies enter that do not sustain current product and process practices, there is the possibility for

[6] Lafrance, Martin and Jérôme Doutriaux. "Sustained success through the management of core competencies: An Empirical Analysis." Technology Management: The New International Language. Institute of Electrical and Electronics Engineers, Inc., 1991: 141-144.
[7] Gordon, James C. and Aidan C. Gordon. "Outsourcing: Focusing on Core Competencies by Leveraging Resources." Managing Virtual Enterprises: A Convergence of Communications, Computing, and Energy Technologies – Proceedings of International Conference on Engineering and Technology Management. August 10-20, 1996. Institute of Electrical and Electronics Engineers, Inc., 1997: 163-167.
[8] Qingrui, Xu, et al. "Putting Core Competencies into Market: Core Competence-Based Platform Approach." Proceedings of 2000 IEEE Engineering Management Society: EMS-2000. Institute of Electrical and Electronics Engineers, Inc., 2000: 173-178.
[9] Christensen, Clayton M. The Innovator's Dilemma. Boston, Massachusetts: Harvard Business School Press, 1997.

destruction of the current market.[10] If a large quantity of resources were expended in the development of the current competencies, a disruptive technology can have a disastrous financial effect on an organization. This effect can be intensified if customers demand an immediate technological shift.

While the risk of disruptive technologies can never be completely adverted, organizations that have expertise in knowledge management and that maintain well structured best practices repositories can position themselves to meet the change in the market. Knowledge management will allow an organization to anticipate industry trends. This will enable the organization to develop competencies where there are new synergies across product lines.

Best practices based competencies can offer an organization a performance advantage over competitors. However, this can only occur when the competencies are accessible to personnel, limited in mobility and updated with frequency. These strategic resources can create a competitive advantage when developed for technologies that have a long-term profitable life and when created with flexibility to be updated with the advent of disruptive technologies.

Increased speed in the market fosters an environment where competitive advantage is driven by the ability of an organization to rapidly learn new competencies when novel technologies appear.[11] Successful organizations will develop best practices based competencies using a framework that enables differentiation from the competition to gain competitive advantage. These competencies will be developed utilizing the best knowledge from inside and outside the organization at any moment in time.

2.2 Competencies Development Frameworks

Institutionalization of organizational knowledge and development of best practices based competencies are not novel approaches to creating a competitive advantage in the market. Organizations typically initiate a strategy that utilizes the available resources to fulfill current or long-term knowledge requirements.

Some organizations develop best practices through the utilization of an external benchmarking framework. This practice ignores internal organizational knowledge based on the belief that best practices are found outside the organization.[12] This is a farsighted view that can cause the institutionalization of practices that are worse than the baseline operation of the organization.

Other organizations utilize frameworks that are too nearsighted. These organizations solely consider internal knowledge and create structures that enable competencies to be continuously reused allowing for speed-to-market.[13] However, these competencies often do not reflect the best

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[10] Walsh, Steve and Bruce Kirchoff. "Disruptive Technologies: Innovators' Problem and Entrepreneurs' Opportunity." Proceedings of 2000 IEEE Engineering Management Society: EMS-2000. Institute of Electrical and Electronics Engineers, Inc., 2000: 319-324.
[11] O'Dell, Carla and C. Jackson Grayson. "Identifying and Transferring Internal Best Practices." American Productivity & Quality Center White Paper. Houston, Texas: American Productivity & Quality Center, 2000.
[12] Cross, Rob and Lloyd Baird. "Technology is Not Enough: Improving Performance by Building Organizational Memory." Sloan Management Review. 41.3 (Spring 2000): 69-78.
[13] Powers, Vicki J. "Xerox Creates a Knowledge-Sharing Culture Through Grassroots Efforts." Knowledge Management in Practice. 1.18 (Fourth Quarter 1999): 1-4.

practices in the industry, which can be incorporated through external knowledge detection. This can cause the knowledge institutionalized to become obsolete, leaving the organization speeding to market with inferior products and processes.

Some organizations utilize internal organizational knowledge and customer input when creating best practices based competencies.[14] The inclusion of external knowledge in the form of customer requirements and preferences will enable created competencies to be utilized to better serve the end users. However, this competency development strategy does not take advantage of the best practices in the industry through external knowledge detection.

Other organizations attempt to incorporate all available information. These organizations institutionalize internal organizational knowledge, incorporate external industry knowledge and integrate customer-supplied product knowledge. However, the full advantage of the acquired information is seldom achieved. Instead of reducing the information to practice, these organizations use simulation and modeling to verify that the knowledge is valid.[15] While this framework is better than the nearsighted internal knowledge institutionalization and farsighted external knowledge detection, it does not utilize experimentation to gain the learning that is essential to developing competencies.

2.3 Preferred Development Framework

There are three general categories of organizational knowledge. The first type, specific knowledge, is information that is restricted to a particular technology or discipline. The second type, integrative knowledge, is comprised of integrated specific information. The third type, deployment knowledge, is obtained through the utilization of specific and integrative knowledge.[16]

Specific, integrative and deployment knowledge are all required for competencies development. Specific and integrative knowledge will be realized when internal information is institutionalized. However, to obtain deployment knowledge the specific and integrative knowledge must be put into practice through experimentation or production.[17]

Beyond internal organizational knowledge, external knowledge must also be institutionalized for the competencies to be effective. The best of the internal organizational knowledge and the external industry knowledge must be put into practice for the organization to obtain the competitive advantage that is sought.

In order to gain competitive advantage, institutionalization of best practices based competencies is required. Additionally, to assure that the established competencies reflect best practices, internal

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[14] Elliot, Susan. "Brøderbund Builds Strong 'Case' for Internal, External Knowledge Sharing." Knowledge Management in Practice. 1.14 (Fourth Quarter 1998): 1-8.
[15] Harrison, Tracy Lynn. " Building Core Competencies in Auto Body Panel Stamping Through Computer Simulation." Master of Science Thesis. Cambridge, Massachusetts: Massachusetts Institute of Technology, 1992.
[16] Parrup Nielsen, Anders. "Outsourcing and the Development of Competencies." PICMET '99: Portland International Conference on Management of Engineering and Technology. Institute of Electrical and Electronics Engineers, Inc., 1999: Volume 1 59.
[17] Linton, Jonathan D. and Steven T. Walsh. "How Do Firms Perform Effective Competency Development." PICMET '99: Portland International Conference on Management of Engineering and Technology. Institute of Electrical and Electronics Engineers, Inc., 1999: Volume 2 42-46.

knowledge capture, external knowledge detection and developed practice experimentation is essential.

2.4 Chapter Summary

This chapter has developed the rationale for institutionalizing organizational competencies through a discussion of potential risks and benefits of such an effort. The frameworks generally used to develop best practices based competencies were introduced. The limitations of these frameworks were also detailed. The chapter concluded with a brief discussion of the preferred components of a framework for developing competencies.

Competency Development Framework

3.1 Proposed Competency Development Framework

Developing best practices based competencies within an organization requires a framework that fosters incorporation of the best knowledge and experimentation for organizational learning. A proposed framework that encompasses these requirements is visually represented in *Figure 1*.

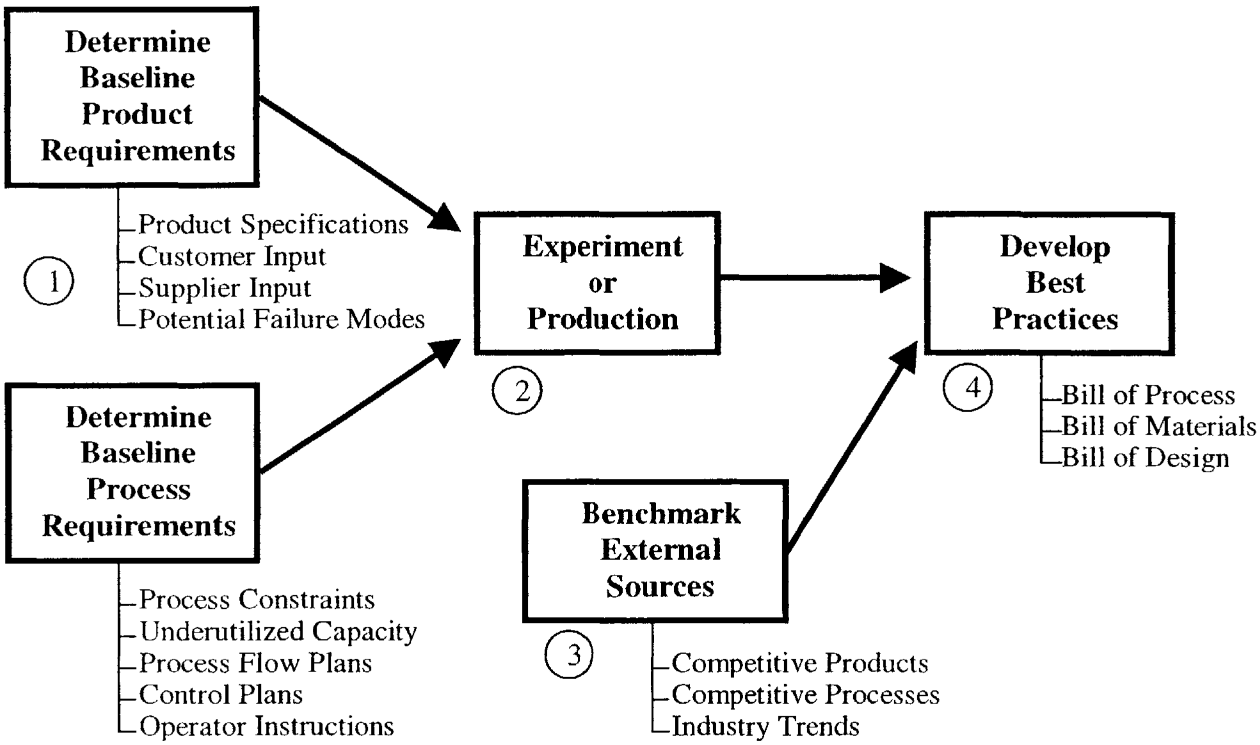

***Figure 1.* Competency Development Framework**

Internal specific and integrative knowledge is included in the best practices based competencies development through the first process step, determine baseline process and product requirements. This framework step also assures that information from the supplier end to the customer end of the supply chain is incorporated. The second process step of the framework achieves assimilation of deployment knowledge through experimentation or production. In the third process step of the framework, external knowledge is detected through benchmarking. The final step of the framework process integrates all of the acquired information to develop best practices based competencies for the organization. Persistently replicating the framework to continuously improve the best practices based competencies will assure that the repository contains the capabilities required to maintain a competitive advantage.

3.2 Determination of Baseline Requirements Rationale

In the first step of the framework, information from the entire supply chain is discovered. This includes supplier-provided technology knowledge, internal organizational knowledge and customer-provided product knowledge. This information represents the baseline knowledge resident within the organization's supply chain.

Suppliers are engaged to create capabilities where organizations have limited synergies in support of best practices based competencies development. Utilization of supplier competencies allows an organization to maintain a competitive advantage in products delivered and cost structure. However, this arrangement causes a strong organizational dependency on suppliers.

Suppliers' technological competencies are essential to the fulfillment of customer requirements. Therefore, suppliers should be instrumental in baseline requirement determination to assure that the corresponding capabilities are acknowledged and possessed.[18] Concurrence on baseline requirements will assure that best practices based competencies can be used in conjunction with supplier capabilities to satisfy customer requirements.

Organizations have internal organizational knowledge that can aid in excelling in the market by fulfilling customers' expectations. However, organizations often confront an imposing challenge in classifying, storing and standardizing the information so that it can be utilized to gain a competitive advantage. Effective management of information promotes sharing and creating knowledge. It also enables the revelation of codifiable and tacit knowledge that can lead to best practices based competencies development.

Capturing best practices in a methodically structured manner through analytical or experimental means initiates institutional learning. This will foster support for further knowledge capture and momentum for competency development throughout the organization.[19] At a minimum, internal knowledge discovered can be employed to represent a baseline of the current operations of the organization. Additionally, comprehending the advantages and disadvantages of internal organizational knowledge can prevent institutionalization of practices that are worse than the baseline operation of the organization.

The adage of meeting the customers' expectations has shifted to exceeding the customers' expectations. Speed in the market requires organizations to adapt to rapidly changing market demands. This competitive market also requires organizations to effectively predict and address customer needs. Maintaining a competitive advantage entails building superior processes, advancing product performance, improving product quality and maximizing organizational effectiveness. [20]

In order to achieve this competitive advantage, organizations must concentrate on understanding and documenting knowledge about their customers. This knowledge should be utilized in the development of best practices based competencies to assure that the capabilities of the

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[18] Nellore, Rajesh et al. "Specifications—Do We Really Understand What They Mean?" Business Horizons. 42.6 (November/December 1999): 63-69.
[19] Miller, D. "A Preliminary Typology of Organizational Learning: Synthesizing the Literature." Journal of Management. 22.3 (May/June 1996): 485-505.
[20] Haeckel, Stephen H. Adaptive Enterprise: Creating and Leading Sense-and-Respond Organizations. Boston, Massachusetts: Harvard Business School Press, 1999.

organization are aligned to support customer needs. Incorporation of customer-supplied information in competency development signals that there is a clear understanding in the organization of the expectations of the customers.

3.3 Experiment or Production Rationale

Knowledge management is an important component of competency development. This component allows for the best information in the organization to be acquired and controlled. However, without verifying the organization's ability to put best practices based competencies into practice, there is little likelihood that the capabilities will lead to a competitive advantage.

In the second step of the framework, potential competencies are verified through experimentation or production. This step allows for the confirmation of an organization's ability to exploit the best practices. If confirmation does not occur, the outcomes of the experimentation offer information regarding the adaptation required in order to create legitimate best practices based competencies.

Experimentation or production alone is a poor basis for learning best practices and institutionalizing competencies. Experimentation without baseline requirements attains limited organizational learning. Unforeseen dynamics and misperception of results will confound unstructured experimentation or production.[21] Concentrated experimentation rooted in determined baseline requirements enables an organization to verify that there are appropriate best practices. These practices can then be transferred across an organization and utilized in the development of competitive advantage competencies.

Validating abilities through experimentation or production should be completed internally by the organization, externally by suppliers and jointly by both the organization and suppliers. The direct result of these efforts will be novel and creative solutions for developing products and processes. Individual and joint experimentation will also shorten the learning curve allowing an organization to introduce improved products in the market faster in order to gain a sustainable competitive advantage.

3.4 Benchmarking Rationale

Achieving and maintaining a competitive position in the global market requires an awareness of the competition and their capabilities. To remain competitive, an organization must be able to continuously improve to become and remain one of the industry leaders. Benchmarking is a means to compare the capabilities of the organization against those of other industry participants.[22]

There are diverse sets of metrics that can be used to compare industry participants during benchmarking studies. Typical metrics fit into several broad categories including financial performance, organizational performance, quality performance and product performance.

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[21] Lomi, A., E. Larsen and A. Ginsberg. "Adaptive Learning in Organizations: A System Dynamics-Based Exploration." Journal of Management. 23.4 (July/August 1997): 561-582.
[22] Compton, W. Dale. "Benchmarking." Manufacturing Systems: Foundations of World-Class Practice. Washington, D.C.: National Academy Press, 1992: 100-106.

Financial performance is evaluated through measuring and comparing typical financial indicators of the industry competitors. These indicators include return on investment, unit cost and unit profit.

Assessing organizational efficiency statistics across an industry's organizations fosters organizational performance comparisons. These statistics include production per hour of labor, machine utilization and work-in-progress.

Evaluating customer satisfaction and internal throughput information in an industry allows quality performance comparisons to be made. This information includes data on customer returns, percent on time deliveries and first time quality.

Product performance is evaluated through comparing features and functionality of products offered by businesses within an industry. Product features comparisons include identifying part counts and material types. Product functionality comparisons include determining field serviceability and operational repeatability.

Often, accurate information is not readily available for competitors' financial performance, organizational efficiency and customer satisfaction. Therefore, it is easier to focus on product performance metrics in benchmarking studies when idea generation is the goal rather than financial and operational comparisons.

In the competency development framework, the benchmarking study is used to gain knowledge to incorporate into best practices based competencies development. Financial performance and organizational efficiency information regarding the competition would be powerful. Since this knowledge is difficult to acquire, the benchmarking study should emphasize product performance. The end goal of the study would be generation of best-in-class product features and functionality that can then be used to determine design and process best practices based competencies.[23]

3.5 Best Practices Repositories

Centralized best practices attempt to increase knowledge exploitation by providing accessible information for the entire organization. This allows the collective knowledge of the entire organization to be utilized in product and process decisions. There are several repository structures that can be utilized by corporations attempting to implement a best practices repository. Three of the most common structures are bill of materials, bill of process and bill of design.

1. Bill of Materials
   - A list of parts required when producing a product.

2. Bill of Process
   - A list of proven manufacturing processes and process sequences required to systematically produce a product.

3. Bill of Design
   - A list of specifications required for the design of a product utilizing proven design fundamentals.

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[23] Ma, Hao. "Of Competitive Advantage: Kinetic and Positional." Business Horizons. 43.1 (January/February 2000): 53-64.

The bills of materials typically exist within an organization. These lists are required to complete standard operating functions. The financial and logistics branches of organizations use these lists to track component cost and delivery. These lists are utilized to assure that products are produced to specifications by the production and quality sections of organizations.

The bill of process is developed to identify and to document the best manufacturing processes and process sequences for each product family. The goal is to determine the best manufacturing systems that can be standardized globally to provide a competitive advantage.[24] Product specific bills of process will be the baseline common manufacturing plan for a specific product.

In some organizations, the bill of process best practices framework is used to gain competitive advantage through shared innovation, consolidated activities and reduced costs. General Motors developed a global bill of process in the corporation's stamping operations.[25] Process standardization through bill of process achieved the corporation's goal of doing more with less to become more competitive in the global market. General Motors has since incorporated the bill of process best practices framework into other sectors of the organization's business with similar success.[26] Appropriately implemented bills of process in other organizations should allow them to acquire similar benefits.

Bill of design factors in the customer-determined requirements and industry trends that effect products and production processes. Design for manufacturing, design for assembly, design for serviceability and design for environment tools are utilized in best practices creation in order to meet the expectations of the product and process stakeholders. These stakeholders include organization personnel, product customers, local governments and interest groups.

The bill of materials, bill of process and bill of design are interconnected. Best practices developed for one framework must be supplied into the development of the others in order to achieve overall best practices. Other information from inside and outside an organization should also be incorporated to create the broadest data set available. This creates an iterative and interconnected development for the three bills as illustrated in *Figure 2*.

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[24] Delphi Automotive Systems. Bill of Process Reference Guide. 2nd ed. Kokomo, Indiana: Delphi Automotive Systems, 1999.
[25] Hallof, Gordon A. "Global Bill of Process – Dies." University of Michigan World Class Manufacturing Seminar Session IV: Factories/Processes Most Likely to Succeed Into the 21st Century Presentation. 5 August 1997.
[26] Cowger, Gary L. Automotive News World Congress Presentation. 16 January 2001.

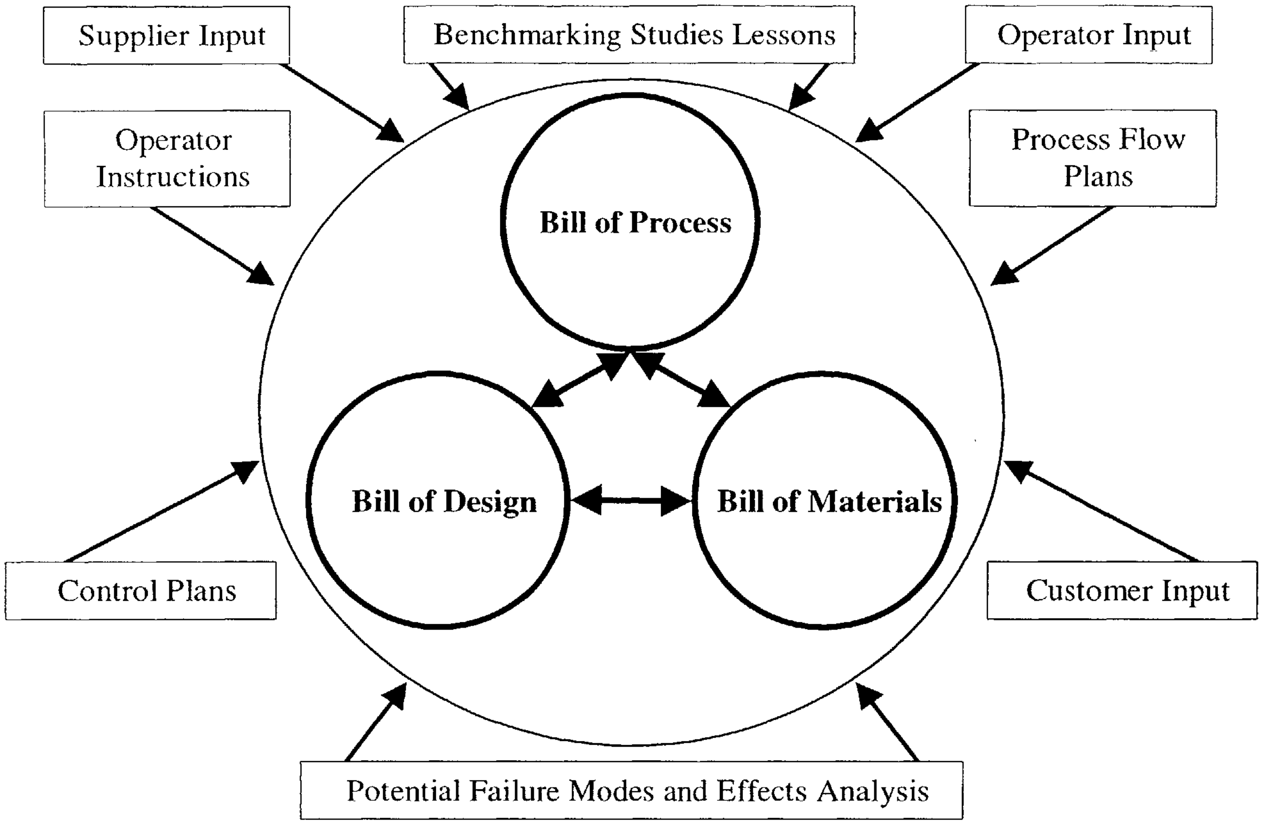

Figure 2. **Iterative and Interconnected Best Practices Development**

3.6 Chapter Summary

This chapter has introduced a proposed four-step framework for developing best practices based competencies. The steps include determination of baseline product and process requirements, experimentation or production, external benchmarking and best practices based competencies development. The rationales behind the first three steps were presented after the framework introduction. The rationale for the fourth step or framework goal, was previously discussed in chapter one. The chapter concluded with a discussion of the interconnected best practices structures that are the goal of the framework.

Chapter 4

Case Study Project Background

4.1 The Changing Sensor Harness Business Environment

At the Mexico Technical Center, Delphi Automotive System's Energy and Chassis Systems division designs, prototypes and launches sensors and actuators. The majority of these sensor products require a wire harness to deliver electrical power to the sensor and to exchange electrical signals between the sensor and the on board computer in vehicle applications. Typically, these are basic harnesses comprised of a vehicle connector, wires and a sensor connector. *Figure 3* shows a typical Energy and Chassis Systems division sensor product.

Figure 3. **Energy and Chassis Systems Division Product**

Historically, the Energy and Chassis Systems division has designed the sensing assembly and procured the wire harness assembly from the Packard Electric Systems division of the organization. As the automotive market's demand has shifted toward electronically enhanced products, the Packard Electric Systems division has redeployed resources to compete in these higher margin markets.[27] Typically, these products utilize technologies that are more complex than the standard wiring used in sensor harnesses. In particular, a transition toward fiber optic and wireless technologies has been made. *Figure 4* shows a typical Packard Electric Systems division fiber optics based product.

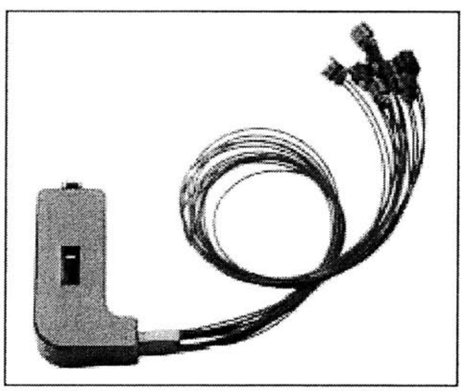

Figure 4. **Packard Electric Systems Division Product**

Timing of this resource rearrangement corresponded to the launch of several new sensor products. The Energy and Chassis Systems division had an immediate need to develop and prototype the analogous harnesses for these sensors. With the division's source concentrating on other electronic products, the Energy and Chassis Systems division was left searching for a new strategy.

Attempts were made to outsource the sensor harnesses to another manufacturer. This failed to find a willing or capable source. Potential vendors contacted were not interested in discussing the sourcing opportunity because they thought the Energy and Chassis Systems division was

[27] Gaut, Steve, and John Pekarek. "Delphi to Accelerate Business Model Shift in 2001." Delphi Automotive Systems Home Page. 12 December 2000. Delphi Automotive Systems. 15 December 2000. <http://www.delphiauto.com/index.cfm?location=2409>.

benchmarking the market for use in internal pricing negotiations. They believed that any good faith efforts on their part would be in vain and that the business would simply return to the internal supplier.

The division's initial solution was to start prototyping harnesses at the same facilities that were developing the sensing assemblies. While this strategy was convenient for the product development teams, the decision was not in the division's long-term best interests. Design and process learnings were not being exploited between the sites. Different locations were using different processes and materials. These differences were being chosen to meet project timelines, to save project money and to utilize team knowledge. However, in the long-term, these differences could increase divisional costs by eliminating the ability to standardize materials, to utilize capacity and to develop best practices.

4.2 Internal Competencies Justification

The timing of the Packard Electric Systems division's resource rearrangement corresponded to the launch of several new sensor products. The Energy and Chassis Systems division had an immediate need to develop and prototype the harnesses for these sensors. With the division's source concentrating on other products, there was at least a temporary need for capacity, capability and technology from another source. This appeared to be a good opportunity to outsource. However, when the division attempted to outsource, there was no willing and capable supplier.

While a lack of willing suppliers made the harness prototyping internalization decision for the division, it was strategically the best conclusion. The division's past dependence on the Packard Electric Systems division to supply sensor harnesses made it possible for the division to have limited harness competencies. The division had limited abilities to write complete harness specifications and to identify capable harness suppliers.

In general, the division was not in a good outsourcing situation since it did not fully understand the product.[28] The imperfect competencies in harness specification reduced the division's ability to determine if a supplier had delivered harnesses to specification. This inability could cause costly quality spills if supplier introduced defects were inadvertently passed on to the customer. Similarly, given the timing of the resource redeployment, there was not adequate time to develop a new capable supplier. Even if there was time, the limited competencies of the division could cause a garbage-in-garbage-out phenomenon in supplier development, which could cause defects to be passed on to the customer.

Further strengthening the need to develop internal competencies was the long-term outlook of the automotive components market. In sensor products, the customer-determined customization is done in the harness through differences in harness length or vehicle connector geometries. As automotive systems become more electronically enhanced and automotive electrical architectures allow for more electronic customization, customers will want to customize using electronics. Embedding printed circuit boards inside the harness connectors is an anticipated method of creating 'smart' sensors customized to meet customer-determined requirements.[29] In order to meet

[28] Fine, Charles H., and Daniel E, Whitney. "Is the Make-Buy Decision Process a Core Competence?." Cambridge, Massachusetts: Massachusetts Institute of Technology Center for Technology, Policy, and Industrial Development, 1996: 21.
[29] Ward, Daniel K., and Harold L. Fields. "A Vision of the Future of Automotive Electronics." Detroit, Michigan: Society of Automotive Engineers, Inc., 2000: 1-3.

this latent market need in the future, thorough understanding of the design specifications and the manufacturing processes for the harness should be developed within the organization.

4.3 A Project to Meet the Sensor Harness Competency Need

The Energy and Chassis Systems division's internal competencies for wire harnesses needed enhancement in order to meet the needs of new sensor programs. A project was started to build these competencies through the development of a prototyping system and a best practices repository.

The prototyping system and the best practices repository would be housed at the Mexico Technical Center. This site was chosen for two reasons. First, the labor rate in Mexico allows products with high manual assembly content, such as harnesses, to be made cost effectively. Second, the Mexico Technical Center had been chosen by Delphi Automotive Systems to be the center for sensors and actuators in the corporation's global plans. Therefore, for the long-term global strategy, the prototyping system and best practices repository belong at the technical center.

Since there are a large number of different sensors and sensor families produced by the division, the decision was made to start with one family of sensor products to limit the magnitude of the project. This decision would give the project more focus enabling the realization of accomplishments in the short project period. It was also a sound decision from the perspective of long-term initiative success since best practices learned from one family of harnesses could be transferred to other families without having to repeat all analyses.

4.4 The Project Plan

Developing a repository of best practices based competencies and creating a source of prototype harnesses were the general goals of the case study project. Through utilizing the proposed best practices based competencies development framework, both of these goals could be achieved.

The project would start by acquiring the baseline product and process requirements. These requirements would be obtained from the internal documentation of the division with some guidance from the Packard Electric Systems division. Additional information would be solicited from the customers. These customers include the internal customer where the prototypes would be delivered and the potential original equipment manufacturer customers where the final productive products would be distributed. Supplier information would also be requested. This input regarding components and equipment is essential to creating the prototype system requirements.

Utilizing the acquired knowledge, the prototype system would be equipped to produce a variety of harnesses utilizing the best practices within the organization. These harnesses would be delivered to internal customer locations. This prototype capability would be integrated into the system for prototyping already established at the Mexico Technical Center without disrupting delivery of other product samples.

The prototype system's processes, equipment and infrastructure would be created through the utilization of Delphi Manufacturing System methods. These methods include value stream mapping, lean equipment design, people focused practices and lifecycle cost analysis. These tools would be used to develop a prototype build system with the flexibility to be utilized for multiple harness prototyping applications and with the efficiency to be considered the low-cost method for producing limited quantities of harnesses.

Quality statistics from the production at the technical center and assembly information from harness utilization at the internal customers would then be employed to develop lessons learned. Internal best practices for material selections, design guidelines and process decisions would be developed from this information. Benchmarking of the Packard Electric Systems division and other wire product manufacturers would also be used to determine baseline best practices for the division. In *Figure 5*, a flow chart of the project plan is presented.

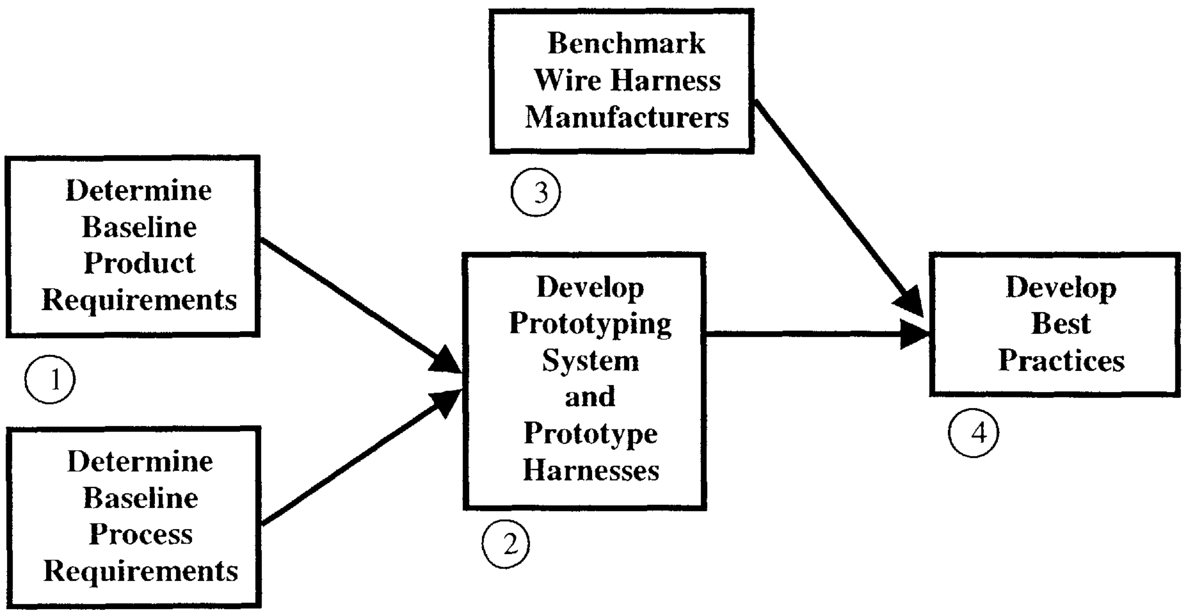

***Figure 5.* The Project Plan**

The project had three major deliverables to be furnished. The first deliverable included all documentation required for the prototype build system. The second deliverable was delivery of built-to-specification sensor harnesses as required by the internal customers. The third project deliverable was the best practices repository.

After project completion, the best practices repository will be used in the development of future harnesses in the product family, and where appropriate, in the development of harnesses in other sensor product families. It will also be used as a template for the creation of other harness product best practices.

4.5 Exhaust Oxygen Sensor Rationale

In order to provide focus in the short project period, the decision was made to concentrate on one family of sensor harness products. This decision would allow the project to accomplish early small wins in the best practices initiative. This decision would also allow the project deliverables to be used as a template for other families of sensor harnesses.

With focus on only one product, it was imperative to choose the most suitable product family. There were harness products that had an immediate need for a prototype source due to the Packard Electric Systems division's decision not to be a source of sensor harnesses. With the time constraints, the project would be most effective if focus was put on a harness that needed a prototype source and that had well-developed requirements. Additionally, if this product's requirements were similar to other product families, it would foster cross product family learning.

The critical sensor family chosen was the exhaust oxygen sensor family of harnesses. This decision was made for several reasons.

1. The author's previous work at Delphi Automotive Systems provided a background in exhaust oxygen sensors that would allow for the immediate commencement of work on the project requirements.

2. Harnesses for these sensors are made of robust materials that can survive the extreme exhaust environment of a vehicle. This would allow technical insights to be transferred to other harness families with similarly strict requirements.

3. There was an urgent need to develop prototyping capabilities for this family of harnesses. There were three new exhaust oxygen sensor products in development. One of these products needed a harness prototyping source immediately.

4. The Clean Air Act of 1970 and subsequent amendments require cars to meet specific exhaust emission standards.[30] The exhaust oxygen sensor is part of the sophisticated emission system that allows vehicles to meet these standards. As the governments of the United States and other countries further restrict emissions, these systems will continue to be needed. These regulations provide the product with a positive future outlook.

5. Research shows that future products based on current architectures of the exhaust oxygen sensor will be capable of meeting next generation customer requirements and government regulations.[31] This further emphasizes the long-term positive outlook of the current product architecture, including the harness architecture.

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[30] "Milestones in Auto Emissions Control." United States Environmental Protection Agency Online. EPA 400-F-92-014 Fact Sheet OMS-12. August 1994. United States Environmental Protection Agency. 11 November 2000. <http://www.epa.gov/otaq/12-miles.htm>.

[31] Yoo, Joon-Ho, et al. "A Study of a Fast Light-Off Planar Oxygen Sensor Application for Exhaust Emissions Reduction." Warrendale, Pennsylvania: Society of Automotive Engineers, Inc., 2000: 1.

4.6 Product Family Portfolio

The exhaust oxygen sensor family produced by Delphi Automotive Systems has one product generation in-the-market and three next generation product varieties in the development pipeline. The in-the-market generation's volumes are decreasing as it is nearing the end of its profitable lifecycle and is no longer considered for new vehicle model contracts. As current vehicle models' contracts expire, it will only be produced as an aftermarket product. Once the replacement parts market no longer demands this product generation, it will be phased out of production.

A customer driven volume mix of the three development pipeline products will replace the in-the-market product, as they are introduced into production in the next vehicle model years. The exhaust oxygen sensor shown in *Figure 6* is the variety currently in-the-market. A product variety from the next generation is shown in *Figure 7.*

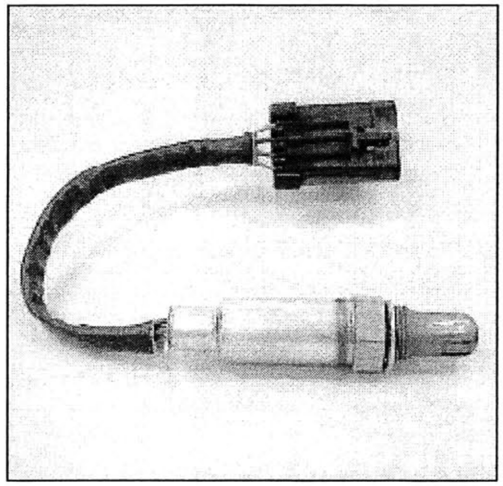

Figure 6. **Current Generation of Exhaust Oxygen Sensor**

Each variation of the exhaust oxygen sensor product utilizes a different sensing technology and has a different sensing scheme. Differences within a product variation account for up to six additional sensor variation subtypes. There are up to ninety part numbers within a sensor variation. Up to forty of these part numbers are within a sensor variation subtype.

This large number of part numbers is the result of customer dictated customization in the harness. However, these part numbers do not reflect fundamental differences in harness design. Rather, the part numbers correlate to different vehicle connector geometries and different harness lengths. Generally, the harnesses across the product family have the same structure.

Figure 7. **Next Generation of Exhaust Oxygen Sensor**

The similarity in harness structure across the product family is an added benefit to best practices development. The diversity of harness lengths and vehicle connectors produced will allow more basic variables to be considered during best practices learning. This will make the project deliverables more powerful when utilized in future best practices development. Focus will be maintained, however, since no fundamental difference in product requirements will have to be addressed during the time constrained project period.

4.7 Chapter Summary

This chapter has explained the background of the case study project. Included in this background was a discussion of the business environment in which the organization is situated. The justification for developing internal rather than external competencies within this organizational environment was also discussed. The case study project plan and deliverables were introduced. This project plan was a project specific replication of the framework proposed for developing and institutionalizing best practices based competencies in an organization. The chapter concluded with an introduction of the exhaust oxygen sensor product family and the rationalization for choosing the exhaust oxygen sensor harness as the project focus.

Case Study Project Utilization of Competency Development Framework

5.1 The Case Study and the Proposed Framework

The case study project plan is a project specific replication of the framework proposed for developing and institutionalizing best practices based competencies in an organization. The goals of the case study project, developing a repository of best practices based competencies and creating a source of prototype harnesses, will be achieved through utilizing the four-steps of the proposed framework.

The first step of the case study project plan is determination of baseline product and process requirements. This will be accomplished through managing the knowledge throughout the product supply chain. The second step, experimentation or production, will be accomplished through developing and utilizing a prototyping system. The third step of the project plan is an external benchmarking study. The fourth step and framework goal will be achieved through the completion of a best practices repository in the form of integrated bills of materials, process and design.

5.2 Product and Process Requirements

The purpose of a sensor harness is to connect the sensor to the on-board computer and the electrical system in the vehicle to allow electrical signals to be interchanged. These signals include sensor power, sensor ground and sensor output.

As shown in *Figure 8*, the harness is made up of three basic system blocks in order to complete these functions.

- The vehicle connection system – typically a plastic connector and electrical terminals
- The signal transfer system – typically wires and electrical terminals
- The sensor connections system – typically an insulating connector and electrical terminals

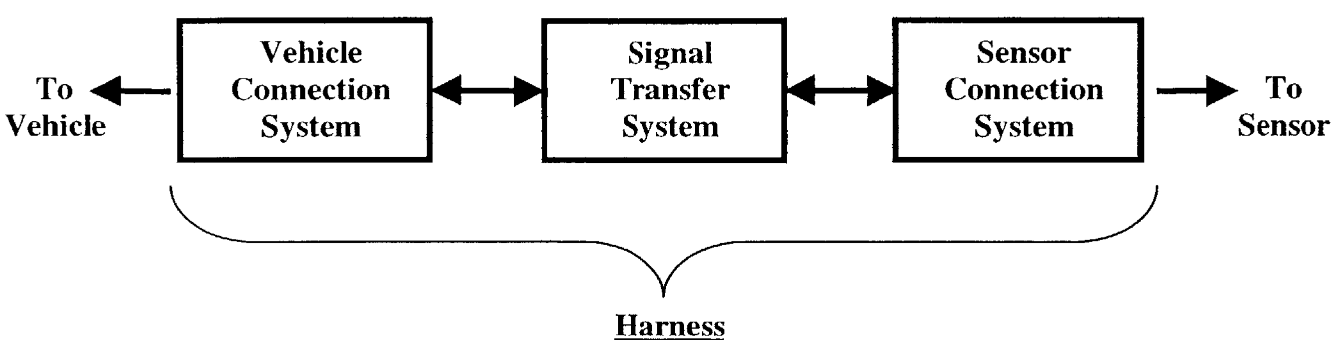

Figure 8. **Harness Basic Sub-Blocks**

The exhaust oxygen sensor is used in vehicles with internal combustion engines that use closed-loop control schemes to meet emissions regulations and to achieve fuel efficiency requirements. Most vehicles currently produced have two exhaust oxygen sensors in each exhaust pipe. *Figure 9* diagrams this automotive system.

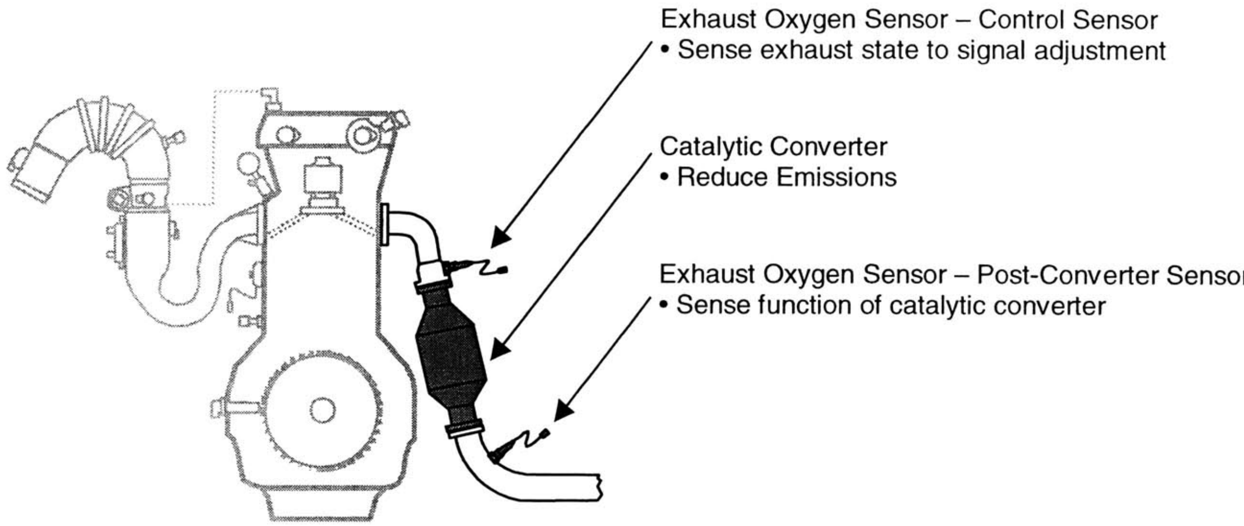

Figure 9. **Exhaust Oxygen Sensor in the Vehicle**

The control sensor, located between the engine and the catalytic converter, feeds the on-board computer exhaust information that allows the system to adjust to release the lowest possible emissions. The post-converter sensor, located after the catalytic converter, is used to assure that the converter is functioning appropriately in order to meet onboard diagnostics standards.

The exhaust oxygen sensor is mounted in the engine exhaust stream. This causes the product's subassemblies to have strict structural requirements. Temperature is a particularly important issue as exhaust temperature can increase to over 900° C.[32] The harness is not directly subjected to these temperature extremes. However, it does have strict electrical, mechanical, temperature and environmental requirements.[33] Internal robust design guidelines, customer application requirements and government regulations dictate these requirements.

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[32] Exhaust Oxygen Sensor Engineering Department. The Oxygen Sensor Book Supplement. Flint, Michigan.: AC Rochester Division-General Motors Corporation, 1992: 3-1.
[33] Exhaust Oxygen Sensor Engineering Department. The Exhaust Oxygen Sensor Book. Flint, Michigan.: AC Rochester Division-General Motors Corporation, 1990: 8-29 – 8-34.

The harness requirements are well developed since the sensor product has a relatively long history and strict regulations. These requirements must be considered when making material selections, designing product components and deciding process flows. A subset of these requirements is listed below.

- Electrical Requirements
  - Operating Voltage
  - Output Voltage
  - Source Current
  - Sink Current
  - Lead Termination Resistance
  - Signal Lead Resistance
  - Power Lead Resistance
  - Insulation Resistance
  - Lead Continuity

- Mechanical Requirements
  - Lead Termination Tensile Strength
  - Lead Termination to Connector Retention Force
  - Vehicle Connector Mating Force
  - Vehicle Connector Retention Force
  - Vehicle Connector Disengage Force

- Temperature Requirements
  - Low Temperature Operation
  - High Temperature Operation
  - High Temperature Stability
  - Time to Temperature

- Environmental Requirements
  - Structure Breathability
  - Withstand Immersion in Oil
  - Withstand Immersion in Coolants
  - Withstand Immersion in Automotive Fluids
  - Withstand Immersion in Salt Water
  - Withstand Impact by Gravel

In addition to these specific structural requirements, there are customer-determined requirements. In general, these customer-determined requirements are in respect to the harness as opposed to the sensing assembly. These differences can include wire lengths, vehicle connector geometries and environmental protective devices.

Accommodating the various customer-determined requirements adds to the complexity of the harness design. There are a limited number of material, design and process combinations that can fulfill both the customer-determined and the structural requirements. In *Figure 10*, an exhaust oxygen sensor harness that meets all the standard specifications and additional customer specific specifications is shown.

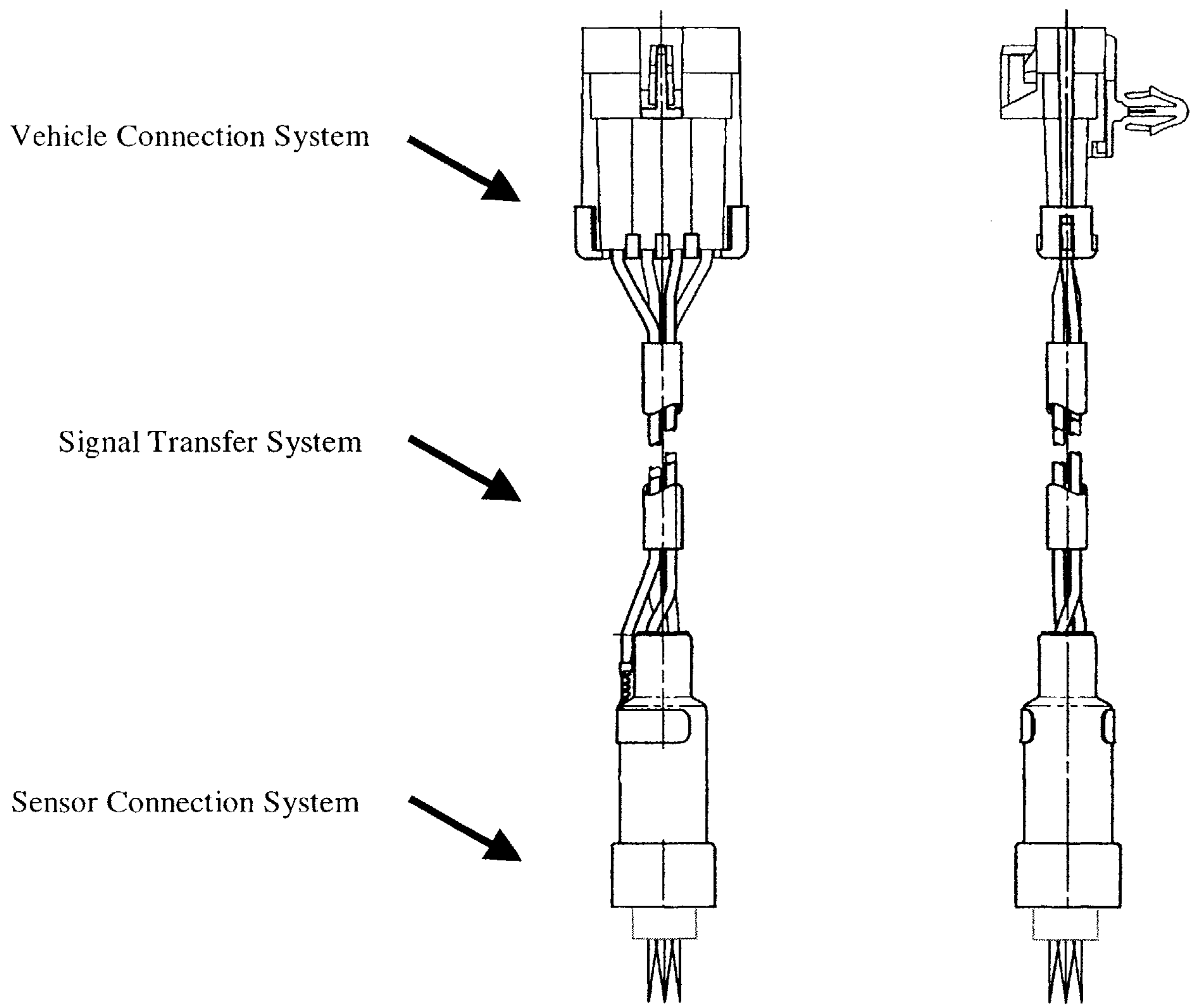

Figure 10. **Exhaust Oxygen Sensor Harness**

The three basic building blocks, the vehicle connection system, the signal transfer system and the sensor connection system, have to be assembled together in order to produce a functional harness that meets the structural and customer-determined requirements. Through years of experience, the Packard Electric Systems division has developed common practices for process flow when manufacturing the exhaust oxygen sensor harness.

The typical process flow utilized is outlined in *Figure 11*.[34] The process flow starts with lead preparation. In this step the wires are cut to the customer-determined length and terminated using a terminal crimp.

The next process step is assembling the vehicle connector. Once assembled, the connector is attached to the wires by snapping the wires' terminated ends into the proper connector cavities.

With the vehicle connection system and signal transfer system attached, the next process step is to attach environmental protection components that shield the wires against heat and insulation cuts.

The next process step is attaching the sensor connector components. These components include electrical insulators and terminal retainers. There are also structural components that support the connection between the exhaust oxygen sensor and the harness.

After the sensor connection system components are attached, the sensor ends of the wires are terminated using a terminal crimp and weld. Then, the terminals are seated in the sensor connector components to complete the sensor connector system. This completes the harness assembly.

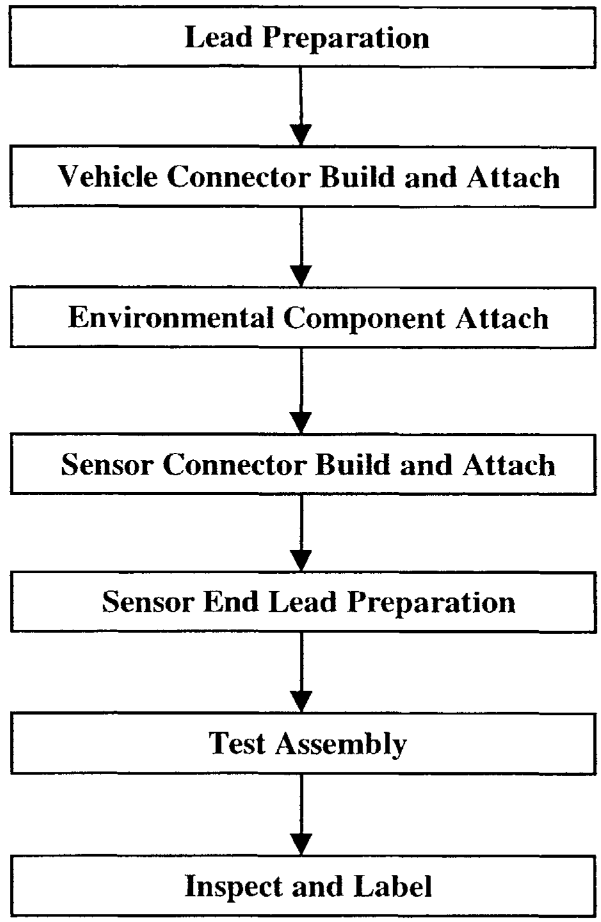

Figure 11. **Typical Harness Process Flow**

The completed assembly is tested for electrical functionality. It is also tested to assure it meets structural requirements.

After passing functional tests, the harness is visually inspected for defects and missing components. Acceptable harnesses are labeled with product identifiers. The labeled harnesses are ready to be packaged and shipped to the customer.

5.3 Prototyping System

The initial goal of the prototyping system was to meet the immediate competency development and prototype source needs of the division by manufacturing prototype harnesses. The system would be equipped to produce harnesses and to deliver them to internal customer locations. The

[34] Szuba, Frank. Packard Electric Systems Division Engineer Interview. 5 September 2001.

system would be integrated into the system for prototyping already established at the Mexico Technical Center.

A further goal of the prototyping system was to create a flexible system that could be utilized for multiple harness prototyping applications with the efficiency to be considered the low-cost method for producing limited quantities of harnesses. Since the system was being developed near the end of a business year, there were limited budget dollars to procure equipment. The capacity required had to be found in underutilized equipment already in the organization. Predictably, this caused the system not to be as flexible or efficient as desired.

Within these constraints, a system concept was developed that would use equipment already available within the organization to fulfill the divisional need. The concept was developed using the best practice process flow from the Packard Electric Systems division. The process flow for this system conceptualization is detailed in *Figure 12.*

The first process step, lead preparation, can be completed manually. However, to maintain the quality and repeatability required by the strict functional requirements of the exhaust oxygen sensor harness, employing automatic wire preparation equipment is preferred. In order to execute the concept, capacity would have to be purchased from the Packard Electric Systems division since the Energy and Chassis systems division did not own the high speed, high volume equipment typically utilized in lead preparation.

Two other process steps required equipment to

Lead Preparation
{Excess Capacity in Packard Electric Systems division}
- Cut leads to length
- Strip and terminate one end and partial strip other end of each lead

↓

Vehicle Connector Build and Attach
{Manual Operation}
- Assemble connector from purchased components
- Snap terminated end of leads into proper connector cavities

↓

Environmental Component Attach
{Manual Operation}
- Cut protective sleeve to length and attach

↓

Sensor Connector Build and Attach
{Manual Operation}
- Attach sensor connector components

↓

Sensor End Lead Preparation
{Excess Equipment from Energy and Chassis Systems division}
- Terminate unterminated end of leads and weld terminations
- Seat terminated leads into sensor connector components

↓

Harness Assembly Test
{Excess Equipment from Energy and Chassis Systems division}
- Test harnesses for electrical and structural function

↓

Inspect and Label
{Manual Operation}
- Visually inspect harnesses and label for identification

Figure 12. **Exhaust Oxygen Sensor Harness Process Conceptualization**

fulfill the system's process concept. These process steps were sensor end lead preparation and harness assembly test. Completion of the sensor end lead preparation required terminal crimp and terminal weld equipment. Accomplishing the harness assembly test required electrical and structural testing equipment.

The terminal crimp equipment capacity was found within the technical center in an underutilized application. New tooling had to be developed to fit this nonstandard crimp press. However, the crimp press had a lean design and was well maintained.

The welding and test equipment were located at another facility that was prototyping harnesses as part of a product development team's project. The welding equipment had been utilized for several applications other than terminal welds. It had additional devices attached to it and occupied a great deal of floor space, which was not in line with the lean and efficient system goals. However, it was capable of completing the terminal welds. The test equipment was only capable of doing a basic electrical functional test. However, it had a lean design and was well maintained.

The other process steps required to assemble the harness in the system concept were manual. These process steps required only basic hand tools such as pliers, wire cutters and rulers. These were low-cost items which were either already available or within the budget for purchasing.

In order to implement the prototype system at the Mexico Technical Center, documentation had to be created. This documentation was required to meet the site's QS9000 quality system standards.[35] Models of the documentation required for the prototype system are presented in **Appendix A**. The documentation required at the technical center falls into four major categories.

1. Control Plans explain which product features need to be evaluated and how often to conduct inspections. These plans detail what tools to use when measuring the features. These plans indicate the acceptable criteria and the reaction plan to follow if the product does not meet the criteria.

2. Process Potential Failure Modes and Effects Analyses describe what are the potential product defects that can occur during processing, what can cause these defects and what effect these defects can have on the customer.

3. Process Flow Plans illustrate the order of process steps in the manufacturing of a product.

4. Operator Instructions clarify how to set-up and operate equipment required to manufacture a product. These instructions also explain how to complete manual operations and quality inspections.

Under the limited budget constraint, it seemed that locating the necessary equipment to implement the prototype system concept was the bottleneck. However, after the equipment was identified there were further delays. The welding equipment looked questionable to Mexican customs and was delayed coming through customs into Mexico.

Further complicating the implementation was the limited budget induced inability to have ownership of the capacity. This lack of ownership made the initial prototype builds contingent on scheduling capacity utilization in the Packard Electric System division and in the underutilized cell

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[35] Automotive Industry Action Group. QS9-3 Quality Systems Requirements. 3rd ed. Southfield, Michigan: Automotive Industry Action Group, 1998.

at the technical center. Predictably, when the capacity was needed in the underutilized cell, it was fully utilized.

Once customs allowed the welder into Mexico, all of the equipment was installed. Limited floor space and lack of capacity ownership did not allow a lean cell to be developed for the prototyping system. This added some waste in the system in the form of unnecessary product movement.

The prototype system was activated to verify equipment operation. This system operation was also used to create a small buffer of components that utilize the shared capacity so that they will not be a bottleneck in future prototype orders. *Figure 13* shows the layout and process for the prototype system implemented.

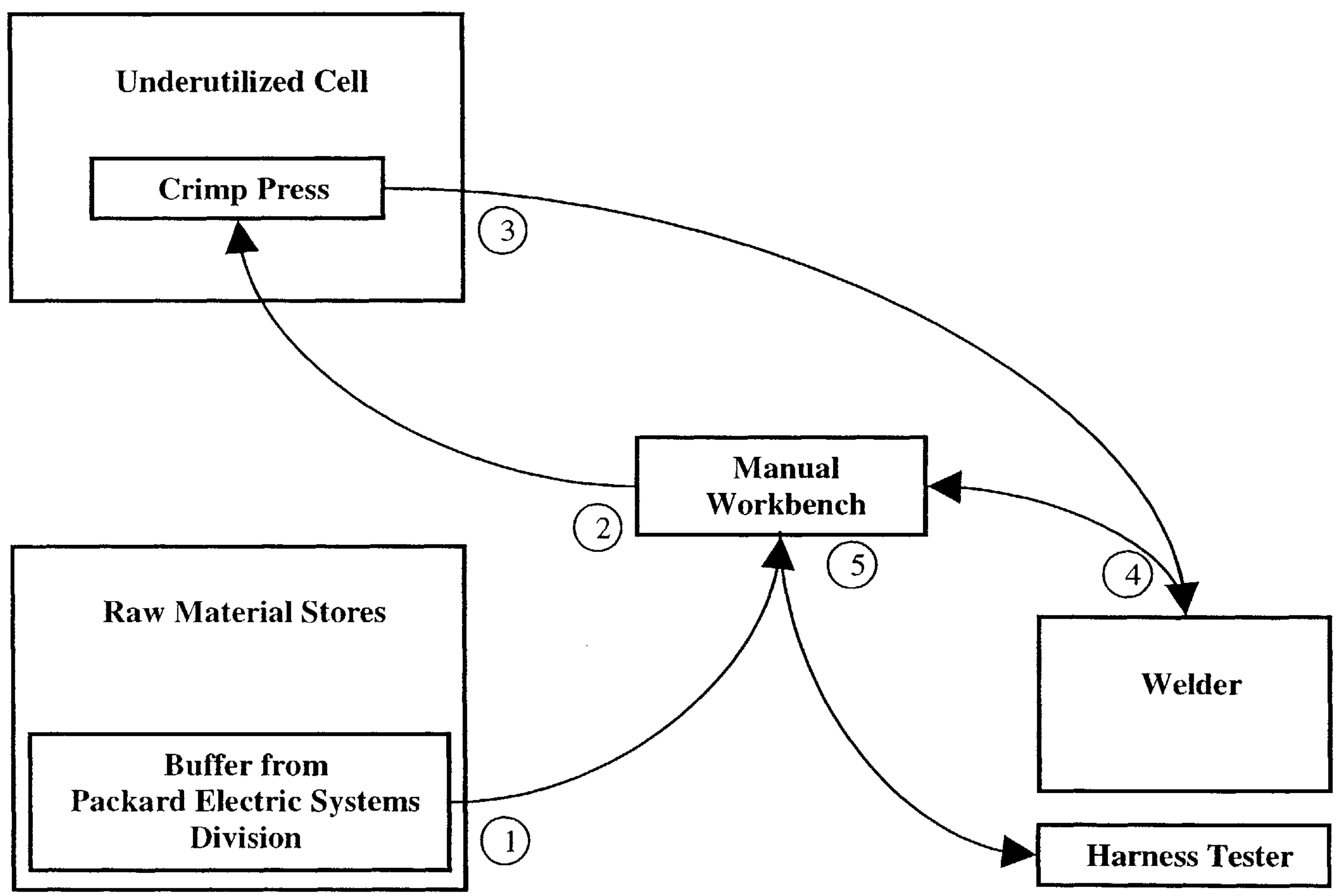

Figure 13. **Implemented Prototype System**

At the end of the project period, over one hundred harnesses from four different customizations were produced using the prototype system and were delivered to an internal customer location. Quality statistics from the production at the technical center and assembly information from the utilization at the internal customers were limited. However, the information acquired provided valuable lessons learned that contributed to best practices development.

Further knowledge gained from harnesses manufactured using the system will be inputted into the development of process best practices and process sequence best practices. These best practices will then be used to efficiently develop manufacturing process sequences for harnesses across all sensor families within the Energy and Chassis Systems division.

In order to achieve the most learnings from the prototype system, it should be reconfigured and equipped for sustainability. A dedicated flexible cell will offer the most in learning through investigating process parameters, testing process sequences and producing multiple harness families. The more flexible the prototype system, the larger the variety of harness families that it can produce. The larger the variety of harnesses produced, the higher the potential of finding universal best practices that can be copied exactly across the entire division.

There are tradeoffs between the prototype system's costs and the long-term harness learnings. However, a small investment can be recouped. With an appropriately flexible and efficient system, future internal and external customer samples can be built and sold to offset the costs. Best practices will also offset the system's costs through reduced product development costs. Further information regarding the prototyping system, including additional recommendations for improvements, is discussed in detailed in **Appendix A**.

5.4 Benchmarking Study

Benchmarking is an effective means to introduce new ideas and concepts into an organization. Benchmarking studies can be utilized in the design and redesign of business processes, products and production systems. For the purposes of this project, the benchmarking study baseline was the current product and production system designs. The goal of the study was to utilize the benchmarking lessons in future product and production system designs. The process flow for the benchmarking study is shown in *Figure 14*.

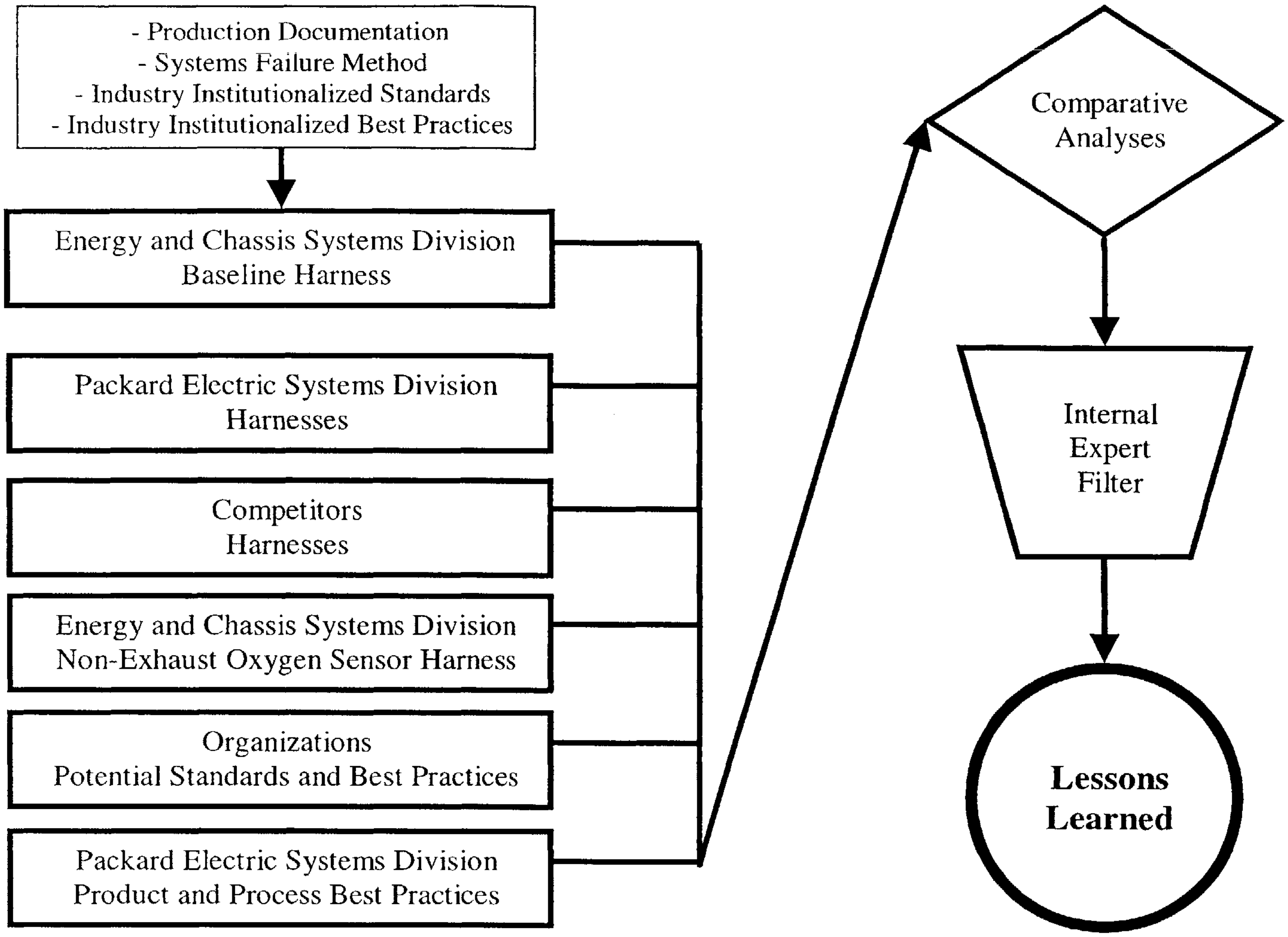

Figure 14. **Benchmarking Study Methodology**

The baseline for the benchmarking study was the current products and production systems in place within the Energy and Chassis Systems division. Organizational information regarding the baseline case for exhaust oxygen sensor harnesses was obtained. This information was in the form of bills of materials, process flow plans, control plans and potential failure modes and effects analyses.

Potential failure modes and effects analyses describe what are the potential product defects that can occur during processing, what can cause these defects and what effect these defects can have on the customer. This information is vital to understanding when a more elegant design is encountered.[36] In order to acquire a complete understanding of the system requirements the seven

[36] Giammatteo, Robert. " System Redesign within Complex, Technically Integrated Products." Master of Science Thesis. Cambridge, Massachusetts: Massachusetts Institute of Technology, 2000.

steps of the Systems Failure Method[37] were used to supplement the potential failure modes and effect analyses.

1. Definition of the System
   - The system is the exhaust oxygen sensor harness. It is comprised of a vehicle connector, a signal transfer system and a sensor connector.

2. Description of System Operation
   - The exhaust oxygen sensor harness connects the exhaust oxygen sensor to the on-board computer and the electrical system in the vehicle. This connection allows electrical signals to be interchanged.

3. Description of the Environmental Conditions
   - The exhaust oxygen sensor harness must withstand temperatures near 900° C. The harness must be able to withstand immersion in oil, automotive fluids and salt water. It must also be able to withstand impact from gravel and road debris.

4. Failure Detection
   - The Energy and Chassis Systems division's warranty information and Packard Electric Systems division potential failure modes and effects analyses were used to determine major system failures. The information was based on long-term customer feedback.

5. Analysis of Failure Mechanisms
   - Failure detection data confirm that the chief failure mechanisms occur at the connections between the vehicle and sensor connectors and the signal transfer system. An additional failure mechanism occurs with structural failures in the signal transfer system.

6. Analysis of Failure Effects
   - The exhaust oxygen sensor harness is an integral part of the exhaust oxygen sensor. Failures in the harness cause a lack of functionality in the entire sensor. A vehicle will continue to operate with a nonfunctioning sensor. However, this operation will be at an increased level of emissions and reduced level of fuel efficiency.

7. Compensation for Failure
   - In the vehicle system, the compensation for failure is a signal of the failure through a 'check engine' light illuminating. Further compensation for failure can be facilitated through corrective actions developed from the lessons learned in the benchmarking study.

This framework provided the baseline of comparison for the benchmark study. It demonstrates where the current product and production processes may contain deficiencies. It also provides a basic understanding of the requirements of the product. These requirements will determine which of the material selection and design parameter lessons from the benchmarking study are compatible with the needs of the exhaust oxygen sensor harness.

Conducting a benchmark study with a broad range of product and production systems presents a better chance that the best practice in the industry will be determined. Since the exhaust oxygen sensor is required on most vehicles, there are various industry participants who design and manufacture the product. This offered the opportunity to benchmark multiple competitors'

[37] Fortune, Joyce, and Geoff Peters. Learning from Failure -- The Systems Approach. New York: John Wiley & Sons, 1995: p. 247.

exhaust oxygen sensor harnesses against the baseline. Additionally, since the focus of the benchmarking study was on the harness, there was no restriction on including other automotive harnesses provided that these harnesses fulfill the basic requirements of the baseline. This allowed for seven harnesses to be included in the benchmarking study.

1. Baseline exhaust oxygen sensor harness from the Energy and Chassis system division
2. In-the-market exhaust oxygen sensor harness from the Packard Electric Systems division
3. Next generation exhaust oxygen sensor harness from the Packard Electric Systems division
4. Competitive exhaust oxygen sensor harness from Bosch
5. Competitive exhaust oxygen sensor harness from Nippendenso
6. Competitive exhaust oxygen sensor harness from NTK
7. Non-exhaust oxygen sensor harness from the Energy and Chassis system division

In addition to industry competitors, information from other organizations outside of Delphi Automotive Systems was gathered. Automotive industry organizations were consulted to determine if there were standards or best practices available. Organizations adding information through this channel included the United States Council for Automotive Research (USCAR) and the Society of Automotive Engineers (SAE).

General electrical industry standard setting organizations and technical societies were contacted to determine if there were standards or best practices available. Organizations adding information through this means included the Wire Harness Manufacturers Association (WHMA), the Institute of Electrical and Electronics Engineers (IEEE), National Electrical Manufacturers Association (NEMA) and American Society for Testing and Materials (ASTM).

The standards already institutionalized within the industry were added to the baseline internal information. This information was used as a starting point for the comparative analyses of the physical harnesses. Based on the failure detection and failure mechanism information developed in the Systems Failure Method, particular attention would be given to the interfaces between the vehicle connector and the signal transfer system and between the sensor connector and the signal transfer system during analyses. Additionally, due to the failure detection and failure mechanism information, special attention during the analyses would be given to the robustness of the signal transfer system.

Ideally, operational evaluation of the competitive products would have been completed as part of the benchmarking study. However, differences in the exhaust oxygen sensors precluded this analysis. Tear down analysis was completed instead.

The competing products were torn down so that the harnesses were isolated from the sensors. Material types utilized were determined. Using the material types and product markings as cues, processes utilized in the assembly of the harnesses were determined. This combination of materials and processes utilized were then used to determine the best practices observed in the benchmarking study.

The combination of exhaust oxygen sensor and non-exhaust oxygen sensor harnesses provided a broad range of product design concepts. The exhaust oxygen sensor harnesses had similar features and materials. However, the differences between the competitive products were substantial enough to indicate potential best practices. The non-exhaust oxygen sensor harness offered other potentially preferred design concepts. Despite the limited differences in the benchmarking study population, potential best practices were determined for each of the three harness sub-blocks.

The data obtained was tabulated and discussed with technical experts within the division. These experts acted as a filter to determine which of the studies findings could be considered current lessons learned for the division. Conversely, these experts also suggested which study findings needed further research and analysis before being institutionalized within the organization. The tabulated information with the additional expert input became the benchmarking study lessons learned.

Lessons from the benchmarking study produced some insights regarding future trends in the industry. While some of these trends can not be immediately incorporated into the exhaust oxygen sensor harness, it is essential to understand the technological direction of the industry in order to build the competencies necessary to compete as these technologies become the customers' needs. Complete details of the benchmarking study and results are presented in **Appendix B**.

5.5 Best Practices Repositories

The knowledge obtained from acquiring the baseline requirements, manufacturing the prototype harnesses and benchmarking the harness industry was analyzed. The lessons learned from this information were used to determine potential best practices. This information was consolidated to become organizational knowledge through the development of a best practices repository. Within this repository, the structures of bill of materials, bill of process and bill of design were developed and integrated.

The bills of materials for the exhaust oxygen sensor products already existed within the division. These lists were required in the organization's financial, quality, production and logistic functions. The product specific bills of materials were integrated into the product specific bills of process and bills of design as these bills were developed.

As dictated by the divisional initiative, the product specific bill of process will be the baseline common manufacturing plan for a specific product. Minimally, it includes bills of materials, process flow plans, control plans and potential failure modes and effects analyses. This documentation was developed employing best practices created from the prototyping lessons and the benchmarking lessons acquired during the project. This knowledge included quality statistics from harness production, assembly information from harness utilization and benchmark information from product comparison.

This product specific bill of process for the exhaust oxygen sensor harness will be utilized to develop future products in order to gain a competitive advantage. A portion of the bill or process that is not considered confidential to the organization is presented in **Appendix C**.

The Energy and Chassis Systems division bill of design initiative was commencing during the project period. As the framework of the bill of design starts to produce best practices, the iterative and interconnected development process between the three bills will produce additional best practices.

The bill of design best practices framework appears to be most relevant when the entire product is considered. Since the interactions between the sensor and harness have a considerable effect on overall product functionality, creating a separate bill of design for the exhaust oxygen sensor harness would not produce advantageous best practices. This interdependence coupled with the limited divisional experience developing bills of design suggested to not undertake an exhaust oxygen sensor harness specific bill of design during the project period.

Information obtained from prototype system harness production and from benchmarking study lessons learned suggests potential best practices for the harness within the exhaust oxygen sensor specific bill of design. These results, which may be later incorporated into a complete exhaust oxygen sensor specific bill of design, are presented in **Appendix D**.

5.6 Chapter Summary

This chapter detailed the case study project utilization of the proposed competency development framework. The four-step process was illustrated through the case study project. In the first step of the project, baseline product and process requirements were determined from throughout the product supply chain. In the second step of the project, experimentation or production was completed through the development and utilization of the prototyping system. In the third step of the project, a benchmarking study was conducted to determine best process and product practices. In the fourth and goal-attaining step of the project, development of a best practices repository in the form of integrated bills of materials, process and design was initiated.

Chapter 6

Conclusions and Recommendations

6.1 Project Outcomes

Installation of a working prototyping system was achieved in the six-month project period. This system was proven capable of producing built-to-specification harnesses for delivery to internal customers. Through the production and delivery of these harnesses, internal best practices were developed. These were used along with lessons learned from the benchmarking study of competitors' harnesses and industry standards to develop a baseline best practices repository for the division.

The project accomplishments will allow the division to continue supplying wire harness prototypes for internal customers in the short-term. The strategic long-term goal of these outcomes is to improve competitive metrics, such as product development costs and speed-to-market.

The author contributed to the project outcomes in several manners. The author located the necessary capacity to install the prototyping system. Additionally, the author assured that the equipment cleared customs to enter Mexico. From the technical perspective, the author redesigned tooling for employment on the underutilized cell and organized installation of all production equipment at the Mexico Technical Center. The production documentation, benchmarking study and best practices repository activities were lead by the author with support from personnel from the Energy and Chassis Systems division.

6.2 Case Study Project Specific Competency Development Framework Extensions

Several market trends have suggested that the viability of automotive sensor wire harnesses is not long-term. While fiber optic applications have appeared in vehicles, fiber optics are not the price and functional ideal for every wiring application. Other apparent replacements include radio frequency technology and cellular wireless technology. These technologies are also not applicable for every vehicle wiring application. Additionally, these technologies are not fully developed for near-term introduction. This suggests that wire harness viability is long-term. Therefore, competencies in wire harness products and processes are fundamental to continue to meet customer needs.

There are additional trends in the automotive market that suggest that a comprehensive understanding of wire harness products and processes is essential to meet emerging customer needs. 'Smart' sensors with customized circuitry embedded in the harness are being introduced. In order to include the embedded circuitry, a thorough product design understanding is required. Similarly, the additional product processing requirements dictated with the new product features necessitate a complete understanding of harness processing.

Another harness effected market trend is the potential industry shift to a higher voltage based vehicle architecture, which will cause a reduction in wire size and in harness weight. This will increase the viability of wire harnesses as they provide less strain on fuel economy. This industry shift will require a comprehensive understanding of harness products and processes in order to transfer them to the new vehicle architecture.

Improvements to the prototype system will allow prototypes to be manufactured and delivered to internal and external customers for multiple families of sensor harnesses. These improvements will promote additional best practices development through experimentation across multiple product families' harnesses. Experimentation across multiple harness families will enable development of a best practices repository for all sensor harnesses.

The bills of materials, bills of process and bills of design included in the best practices repository will enable the organization to rapidly produce new products and to completely utilize global capacity. In the long-term, the cost to implement an improved prototype system will be offset by the ability to sell prototypes to external customers and by creating effective best practices that foster improvements in competitive metrics.

6.3 Competency Development Framework Extension to Other Product Lines

In recent years the automotive components market has switched from a few customers wanting a few high volume models to a larger number of customers wanting low volume customized models. As with many industries, this move to mass customization has forced suppliers to change the manner in which they conduct business.

There are more major changes developing on the industry horizon. The desire for systems that reduce emissions and increase convenience are driving the industry toward a new vehicle architecture. This architecture may incorporate both the current twelve volt technology and a higher forty-two volt technology. Potentially, the architecture will only utilize a single high voltage at the forty-two volt level. This would cause the current twelve volt technology and components utilizing it to become obsolete. [38]

At higher voltage, fuel efficiency gains will be realized through reduction in wire size and inclusion of systems that allow engines to idle when the vehicle is not in motion. The higher voltage architecture will also allow systems that require high power consumption to be incorporated in vehicles such as electric steering. This incorporation will be made without requiring the tradeoff of not including other electronic devices such as convenience computer information and entertainment systems. With these measurable gains, the higher voltage architecture will be adopted. This reality will force suppliers to thoroughly understand their products and processes in order to rapidly redesign and transfer them to the new architecture.

Decreasing all vehicles' effect on the environment is also driving emerging market trends. Recycling the entire vehicle with a strategy of removing everything of value from the vehicle before shredding and using all byproducts after shredding is planned. This strategy is expected to be a reality in the United States in 2004.[39]

When complete recycling and reusing is achievable, there will be endorsements for legislation requiring one hundred percent vehicle recycling. This will force suppliers to thoroughly

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[38] Kobe, Gerry. "Electronics: What's Driving the Growth." Automotive Industry Online. August 2000. 23 March 2001. <http://ai-online.com/articles/aug00/0800f1.htm>.
[39] Diegmann, Wolfang, et al. "Profitable Recycling of Automotive Wiring Harnesses." Environmental Concepts for the Automotive Industry (SP-1542). Warrendale, Pennsylvania: Society of Automotive Engineers, Inc., 2000: 1-4.

understand their products and processes in order to redesign products with recyclable materials and to redesign processes to foster assembly that does not hinder the recycling process.

Another emerging market trend triggered by the environment is the electrical vehicle. While this market trend is currently on the long-term horizon, suppliers have to thoroughly understand their products and processes to rapidly transfer to this new architecture when it becomes the standard.

A more current industry movement has been toward widespread globalization. At a minimum, this compels suppliers to be able to deliver products efficiently everywhere in the world. Particular countries make this challenge more complex with local content regulations requiring a percentage of products sold in a country to be manufactured in that country. This forces more than optimization of the entire supply chain. It also forces suppliers to thoroughly understand their products and processes in order to produce them everywhere in the world at an acceptable profit.

After several record years in vehicle production and sales, a downturn in the major global economies may signal and impending downturn in the automotive industry. Whether this economic downturn threatens the entire industry or individual players, there is the potential for suppliers to feel the financial squeeze as vehicle manufacturers try to secure profits.[40] Suppliers need to thoroughly understand their products and processes in order to correct for the negative effects the financial squeeze will have on the bottom line.

Suppliers should maintain organizational knowledge centers to sustain a thorough understanding of their products and process. This accessible knowledge will allow suppliers to rapidly react to industry changes in vehicle architecture, environmental preservation, market globalization and economic forecast. This knowledge center should contain the best practices for products and processes to allow rapid fundamental changes to be made efficiently. This reinforces the need for extension of best practices development across multiple product families.

When the industry is fairly stable, extension of best practices development across multiple product families will also allow human and monetary capital to be released from re-engineering tasks. This is accomplished by having baseline product design best practices and process sequence best practices from which to commence the redesign. This saves the resource effort of recreating products and processes that have already been institutionalized.

The resources freed from re-engineering tasks can be refocused on product advancement to exceed customer expectations in the automotive market. Resources can also be refocused on development of strategic non-automotive markets in order to diversify the business to protect against any future downturn in the automotive market.

6.4 Recommendations for Long-Term Strategy

The move to mass product customization and the speed of emerging market trends has forced suppliers to change the manner in which they conduct business. In order to meet these challenges in the automotive industry, Delphi Automotive System's Energy and Chassis Systems division needs a strategy that focuses on a broad range of products that can be produced profitably and that can allow the organization to rapidly respond to global customer needs.

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[40] Kobe, Gerry. "Supplier Squeeze." Automotive Industry Online. March 2001. 23 March 2001. <http://ai-online.com/articles/mar01/coverstory1.htm>.

The best practices initiative assists the organization in meeting these challenges through the bills of materials, bills of process and bills of design. This initiative also fosters an organizational culture that enables common product, agile process and lean equipment programs to succeed. The success of these initiatives offers the organization competitive advantages. These advantages enable rapid global customer support. In the short-term, this includes the ability to do business in various global regions as required by local regulations. In the long-term, this includes the ability to grow automotive and non-automotive business in profitable core products.

An effective strategy for the Energy and Chassis Systems division will incorporate these initiatives to make the division an agile and low-cost producer of sensors and actuators worldwide. In order to achieve agility and low-cost, the entire supply chain needs to be optimized.

In the manufacturing system, the optimization must occur across all products and processes to completely utilize manufacturing capacity and reduce structural costs. Common products and processes proliferated globally will enable capacity shifts with global demand shifts that will allow complete utilization of facilities, equipment and personnel. Optimization and commonization in manufacturing systems will increase speed-to-market enabling the organization to meet all global customers' needs. Optimized and commonized manufacturing systems will also promote global collaboration to eliminate effort duplication, share system innovation and reduce manufacturing costs.

A strategy to accomplish manufacturing system optimization is rooted in thoroughly developed product specific bills of process. These bills of process will standardize processes and equipment globally. In contrast to individually optimized products and processes, universal standardization enables utilization of capacity within a product and across products in all global facilities.

Bills of process will be created centrally at technical centers employing global input. Once thoroughly developed, the standardization of the bills of process will be supplied to global bills of process, global bills of materials and global bills of design development. This integration will enable the best product design to be matched with the best process practices to produce it. These well designed product and process pairings can then be proliferated globally. This facilitates manufacturing in any region of the world using common capacity and common practices. A flowchart illustrating this competency development strategy is shown if *Figure 15*.

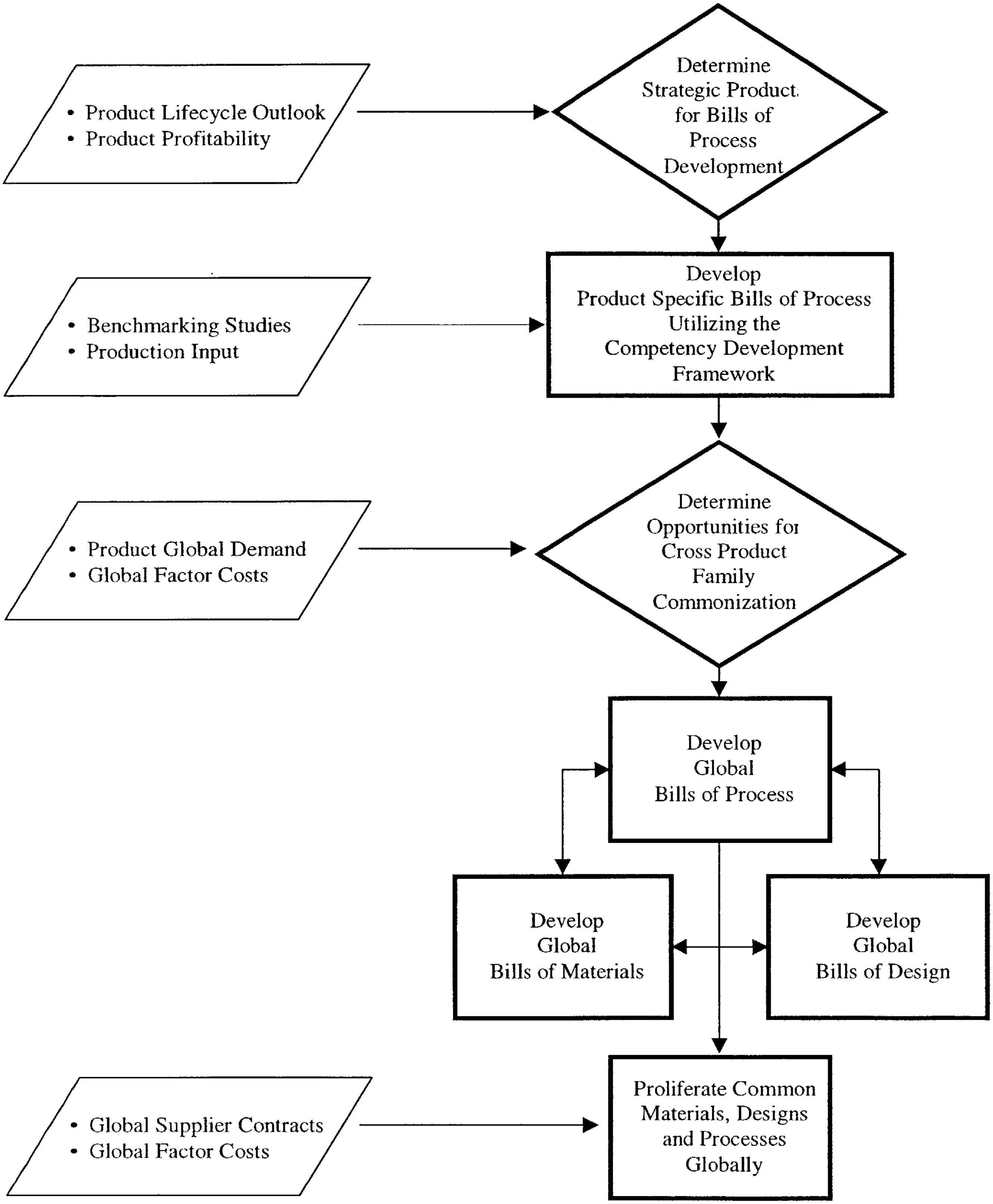


Figure 15. **Competency Development Strategy**

Best practices development across multiple products will allow an organization to have accessible knowledge to rapidly and efficiently react to fundamental changes in the global market. When the market is fairly stable, best practices development will allow resources to be released from re-engineering tasks. The resources can be refocused on product advancement in the core markets of the organization. This refocus can be utilized to exceed customer expectations and diversify the business to protect against any future downturn in the core markets.

6.5 Chapter Summary

This chapter detailed the project outcomes and author contributions. Suggestions were presented for potential project extension and rationales were offered for further framework utilization. The chapter concluded with a discussion of a proposed long-term strategy for best practices based competencies development.

Appendix A

The Prototyping System

The Prototyping System

The Prototype Order System

Several divisions of Delphi Automotive Systems use the Mexico Technical Center facilities to prototype products. Since there is a large volume of products being manufactured at the technical center, there is a process in place to control and track prototypes in progress.

The exhaust oxygen sensor harness build and test processes developed as part of this project had to be incorporated into the prototype order process. This incorporation was necessary to allow other prototypes to be completed according to schedule without disruption. Within the prototype order system, installation of a working prototyping system was achieved in the six-month project period. This system was proven capable of producing built-to-specification harnesses for delivery to internal customers.

The extensive prototype order system employed at the technical center is fundamental to assuring that only built-to-specification prototypes are shipped to the customer. However, the additional control steps expand and complicate the prototype process. A value stream map of the detailed process required to complete a prototype order is presented in *Exhibit A*. An additional value stream map that illustrates the detailed process to complete the build and test portion of a prototype order is shown in *Exhibit B*.

The Prototype System

At the end of the project period, over one hundred harnesses representing several customizations were produced using the prototype system. These harnesses were delivered to an internal customer location. Quality statistics from the production at the technical center and assembly information from the utilization at the internal customer were used to improve the implemented system.

In *Exhibit C* and *Exhibit D*, the manufacturing sequence and prototype system are presented respectively. The exhibits illustrate the system as it was operating at the end of the project period. This system contains two slight modifications from the original system implemented.

The first modification to the system, was removal of the partial wire strip process at the Packard Electric Systems division. This process step was replaced with a wire strip process prior to the terminal crimp process and was completed using wire strip capacity in the underutilized cell. The partial strip process was removed due to the potential of insulation disengagement during shipping causing wire strand damage. Wire strand damage can cause the exhaust oxygen sensor harness to fail prematurely in the field.

The second modification to the system, was a change in capacity purchased from the Packard Electric Systems division. The Energy and Chassis Systems division had difficulty in procuring vehicle connector components. Since the Packard Electric Systems division manufacturers a wide variety of harness products, the division had these materials readily available. The capacity purchased was shifted to include wires that were cut, stripped, terminated and attached to a vehicle connector. This purchased capacity was stored in a buffer so that it would be available when prototype orders required it.

Future production and quality feedback data will be employed to make further modifications to the prototype system to maintain system sustainability. Additionally, system modifications will be made to improve flexibility and capability in order to experiment when developing future process best practices.

The Prototype System Documentation

In order to implement the prototype system at the Mexico Technical Center, documentation had to be created. This documentation includes control plans, process potential failure modes and effects analyses, process flow plans and operator instructions.

Control plans explain which product features need to be evaluated, how often to inspect and what tools to use to measure. These plans indicate the acceptable criteria and the reaction plan to follow if the product does not meet the criteria. A sample of a purchased material control plan for an exhaust oxygen sensor harness component is presented in *Exhibit E*. An example of a partial process control plan for the exhaust oxygen sensor harness is in *Exhibit F*.

Process potential failure modes and effects analyses describe what are the potential product defects that can occur during processing, what can cause these defects and what effect these defects can have on the customer. A partial process potential failure modes and effects analysis for the exhaust oxygen sensor harness is presented in *Exhibit G*.

Process flow plans illustrate the order of process steps in the manufacture of a product. These plans reiterate the critical features described in the control plans. *Exhibit H* displays a portion of the process flow plan utilized in producing the exhaust oxygen sensor harness.

Operator instructions clarify how to set-up and operate the equipment required to manufacture a product. These instructions also explain how to complete manual operations and quality inspections. At the Mexico Technical Center, instructions are written in English and Spanish to be functional in the multilingual environment. Operator instructions for one process step required to assemble the exhaust oxygen sensor harness are presented in English in *Exhibit I* and in Spanish in *Exhibit J*.

Recommendations for Prototype System Improvements

In order to achieve the most learnings from the prototype system, it should be configured and equipped for flexibility, capability and sustainability when budget dollars are available. A flexible cell will offer the most in learning through investigating process parameters, testing process sequences and producing multiple harness families. The more flexible the prototype system, the larger the variety of harness families that it can produce. The larger the variety of harnesses produced, the higher the potential of finding universal best practices that can be copied exactly across the entire division.

The equipment resources installed in the prototype system's flexible cell do not need to be extremely sophisticated. The included equipment should incorporate all standard process steps required in making harnesses.

- Lead Preparation
  - Wire dereeler—to remove wire from reel for the cutter
  - Wire cutter—to cut wire to length repeatability
  - Wire stripper—to strip the proper length of insulation repeatability

- Terminal Crimping
  - Crimp press—to crimp multiple terminal types to multiple wire types

- Terminal Welding
  - Resistance welder—to weld terminations when more than a crimp is required

- Harness Testing
  - Electrical tester—to verify electrical continuity
  - Structural tester—to verify weather-tight, breathability and strength features

As investigation and subsequent best practices warrant it, changes should be made to the prototype system. In the short-term, experimentation should be conducted to verify the need for welding of termination crimps in harnesses. If research verifies that the weld is redundant, this process step should be removed from the bills of process and the prototype system.

As trends in the industry advocate the development of new technologies, processes should be introduced into the system to experiment and build competencies. In the near-term, as the industry prepares to institute 'smart' sensors with embedded circuitry in the harness, a molding machine with overmold capability should be added to the system. This recommended flexible prototype system for near-term installation is illustrated in *Exhibit K*.

There are tradeoffs between the recommended prototype system's costs and the long-term harness learnings. However, a small investment can be recouped. With an appropriately flexible and efficient system, future internal and external customer samples can be built and sold to offset the costs. A flexible sustainable system will offer the opportunity to experiment and develop best practices across multiple families of harnesses. These best practices will also offset the system's costs through reduced product development costs.

Exhibit A. The Prototype Order Process

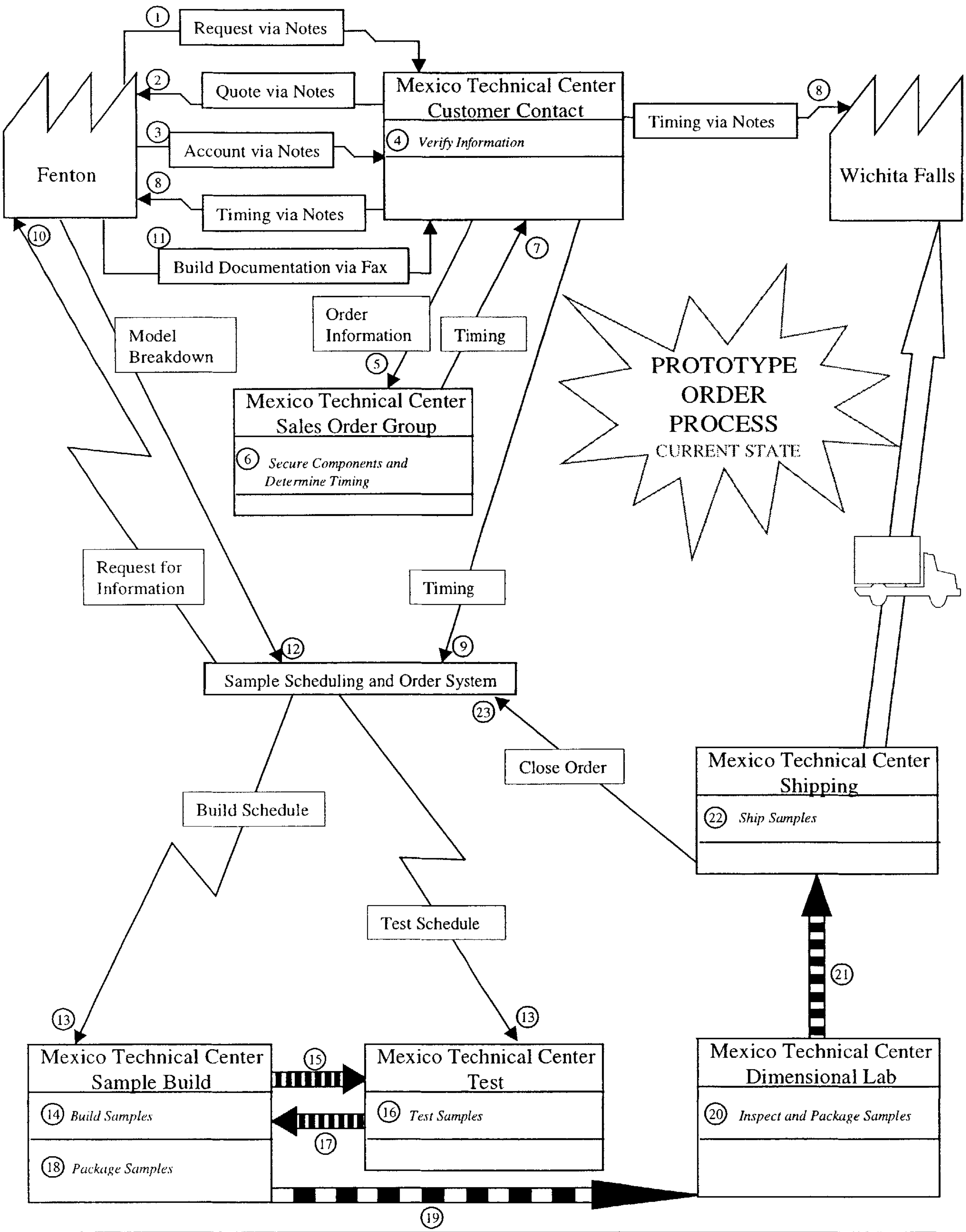


Exhibit B. The Prototype Build Process

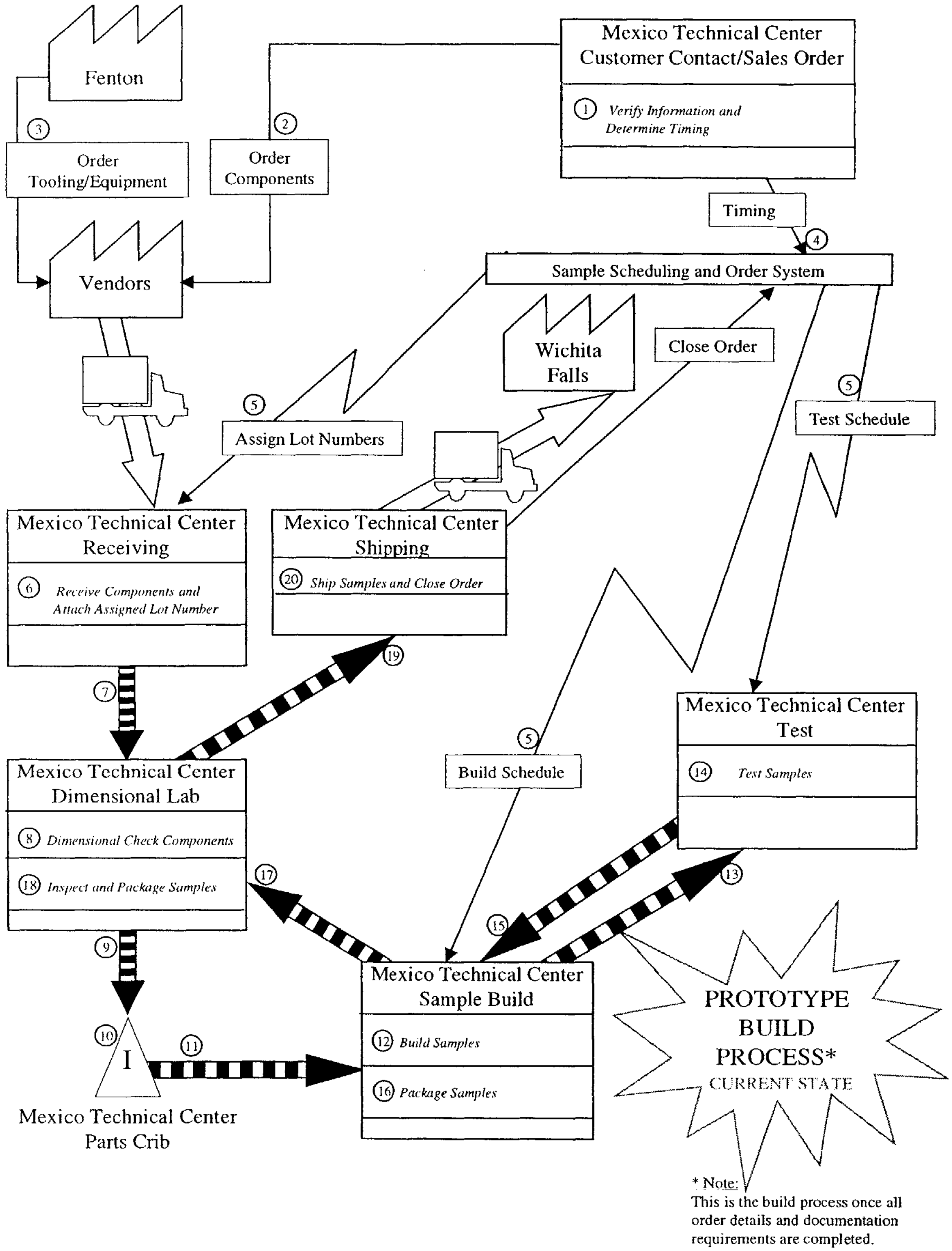


Exhibit C. Manufacturing Sequence Diagram

DELPHI
Automotive Systems

Manufacturing Sequence Chart

Project: Exhaust Oxygen Sensor Harness – Prototyping **Date: 14-Jan-01**

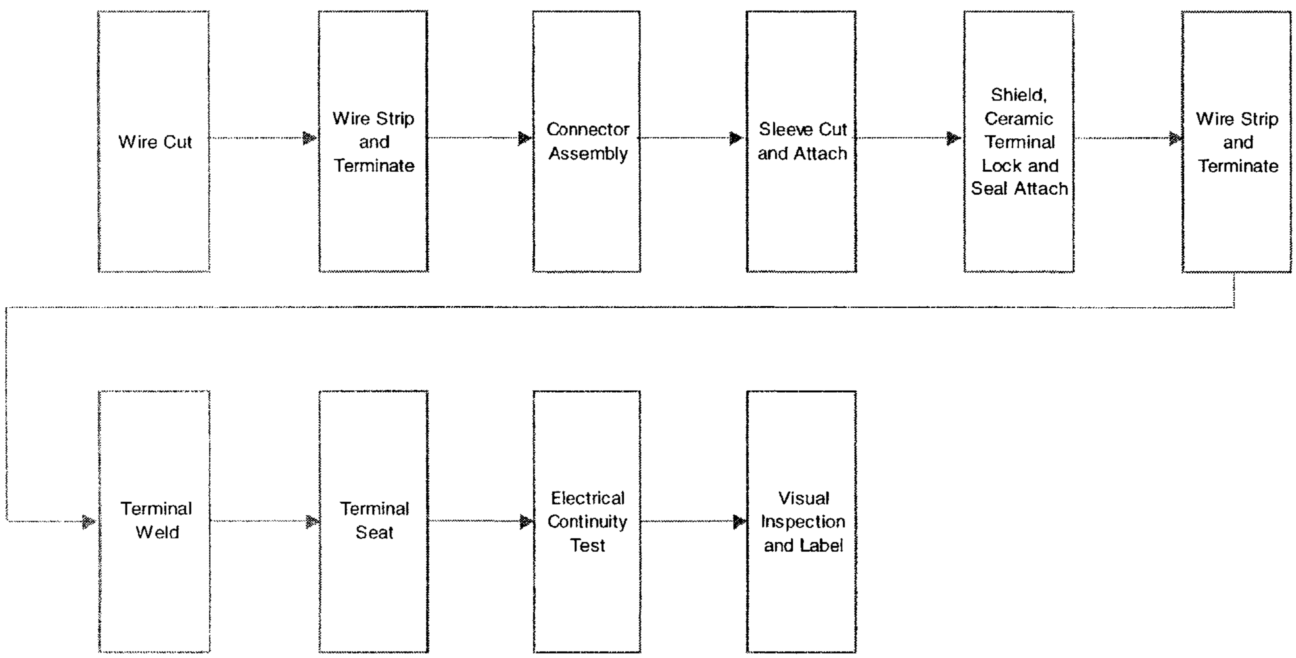


Exhibit D. Prototype System

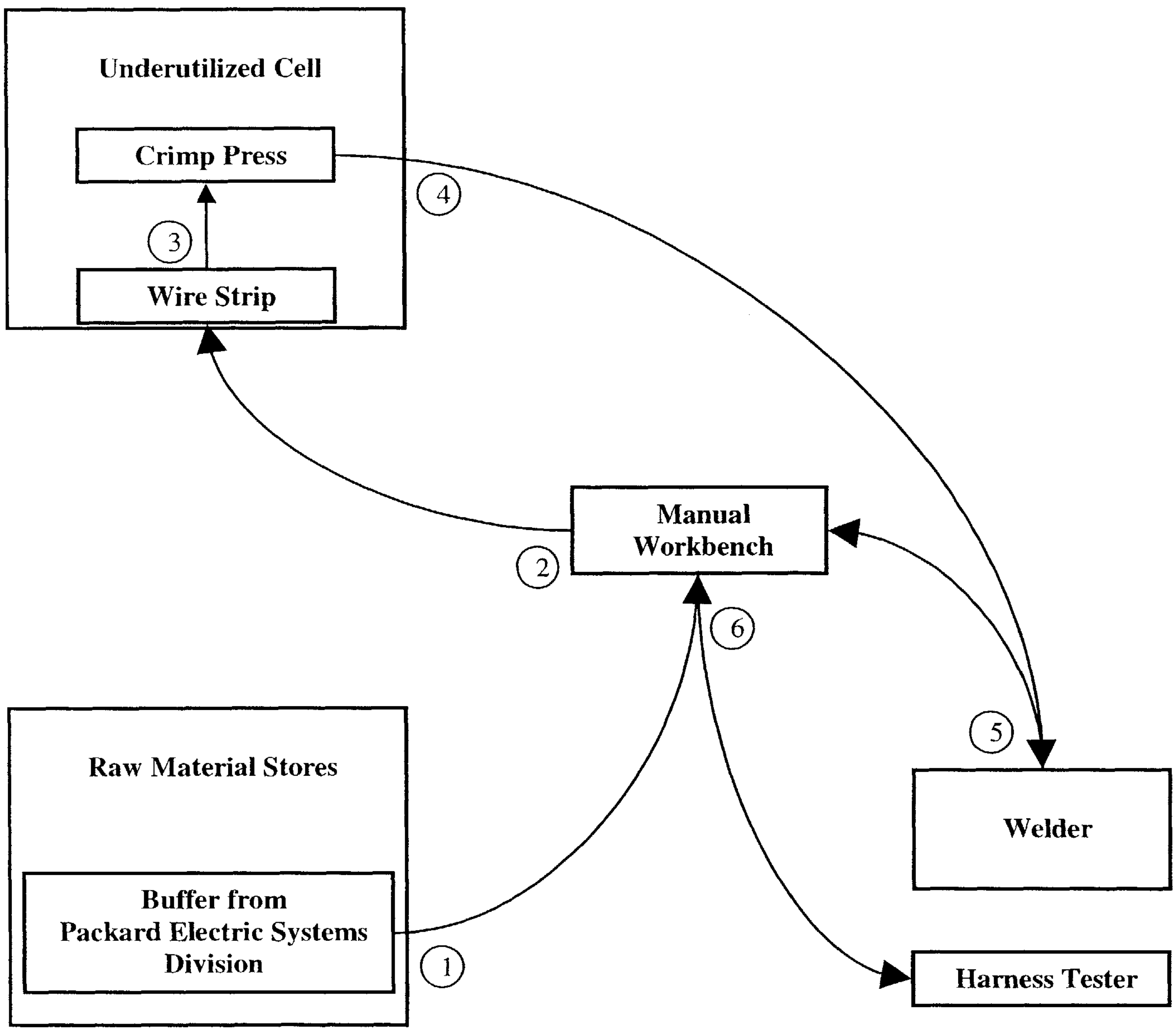


Exhibit E. Component Control Plan

Rutina de Proceso: Plan de control de Proceso /
Process Routing: Process Control Plan

Prototipo/ Prototype ☐	**Pre-lanzamiento/ Pre-launch** ☐	**Producción/ Production**	**Ultima Rev. de Plano/ Print Rev.: Rev. 06**	**Número de Parte/ Part Number: 25329659**

# Cambio / Chg #	Fecha / Date (rev)	Ing. De Procesos /Herramientas / Process /Tool Engineer	Ingeniero de Calidad / Quality Engineer	Nombre de la Parte/Part Name: Exhaust Oxygen Sensor Harness--Shield	Pag/ Page: 1of 1
	07/17/2000	S. Bergman		Nombre del Producto/Product Name: Exhaust Oxygen Sensor	Dept.:
	Fecha / Date (orig)	Aprobación de Ing. Del cliente/Fecha / Cust. Engrg Apvl./Date (If reqd)	Aprob. calidad del cliente/Fecha / Cust. Quality Apvl./Date (if reqd)		
	07/17/2000				
	PCP #			Contacto Clave/Tel/Key Contact/Phone:	
				Planta/Código Prov. / Plant/Supplier Code:	

Equipo Principal / Core Team:

# Op	Descripción de la Operación / Operation Description	Máquina / Machine	Características / Characteristics: No.	Características / Characteristics: Producto / Product	Características / Characteristics: Proceso / Process	Caract. Especial / Special Charact.	Métodos / Methods: Espec. De Producto/Proceso/ Product/Process Specification	Métodos / Methods: Técnicas de Eval./ Medición/ Eval./Measurement Technique	Métodos / Methods: Tamaño de Muestra/ Sample Size	Métodos / Methods: Frec./Freq.	Métodos / Methods: Método de Control/ Control Method	Plan de Reacción / Reaction Plan
00	Receiving Inspection of Shield	Tool 18.79 Plug Gage or Equivalent	1	Shield According to Component Print		◇ 1	Minimum Diameter of 18.79 mm. at a Minimum Depth of 5.0 mm. for the Sensor End Opening	Check Print Dimension Using Plug Gage or Equivalent		Each Lot		-Segregate Suspect Material -Document Quality Issue -Contact Responsible Engineer -Return Out-Of-Spec Material to Supplier

Exhibit F. Process Control Plan {abridged}

Rutina de Proceso: Plan de control de Proceso /
Process Routing: Process Control Plan

Prototipo/ Prototype ☐ **Pre-lanzamiento/ Pre-launch** ☐ **Producción/ Production** | **Ultima Rev. de Plano/ Print Rev.: T6F** | **Número de Parte/ Part Number: EOS Planar Family**

# Cambio / Chg #	Fecha / Date (rev) ⇩	Ing. De Procesos /Herramientas / Process/Tool Engineer	Ingeniero de Calidad / Quality Engineer	Nombre de la Parte/Part Name: Exhaust Oxygen Sensor Harness	Pag/ Page:
	07/17/2000	S. Bergman		Nombre del Producto/Product Name:	Dept.:
	Fecha / Date (orig) ⇩	Aprobación de Ing. Del cliente/Fecha / Cust. Engrg Apvl./Date (If req'd) ⇩	Aprob. calidad del cliente/Fecha / Cust. Quality Apvl./Date (if req'd) ⇩	Exhaust Oxygen Sensor	
	07/17/2000				
	PCP #			Contacto Clave/Tel/Key Contact/Phone:	
				Planta/Código Prov. / Plant/Supplier Code:	

Equipo Principal / Core Team:

# Op	Descripción de la Operación / Operation Description	Máquina / Machine	Características / Characteristics: No.	Producto / Product	Proceso / Process	Caract. Especial / Special Charact.	Métodos / Methods: Espec. De Prodcuto/Proceso/ Product/Process Specification	Técnicas de Eval./ Medición / Eval./Measurement Technique	Tamaño de Muestra/ Sample Size	Frec./Freq.	Método de Control/ Control Method	Plan de Reacción / Reaction Plan
40	Cut Sleeve to Length and Attach	MANUAL			Sleeve Length		For 25335187: 420 mm. +/- 10 mm. For 25335188: 565 mm. +/- 10 mm. For 25340321: 240 mm. +/- 10 mm. For 25340322: 290 mm. +/- 10 mm. For 25340323: 360 mm. +/- 10 mm. For 25342879: 330 mm. +/- 10 mm. For 25343246: 340 mm. +/- 10 mm.	Check Print Dimension Tool Metric Graduated Ruler or Equivalent	1 pc.	100%	Measurement Aid	If wrong length, discard sleeve.
50	Assemble Shield, Ceramic Terminal Lock and Seal	MANUAL			Shield Orientation		Proper shield orientation	Visual Inspection	1 pc.	100%	Visual Aid	If shield oriented wrong, disassemble and reassemble.
					Ceramic Terminal Lock Orientation		Proper ceramic terminal lock orientation	Visual Inspection	1 pc.	100%	Visual Aid	If ceramic terminal lock oriented wrong, disassemble and reassemble.
					Seal Orientation		Proper seal orientation	Visual Inspection	1 pc.	100%	Visual Aid	If seal oriented wrong, disassemble and reassemble.
					Wire Orientation		Each wire in proper seal hole and proper upper ceramic hole No crossed wires between seal and ceramic terminal lock	Visual Inspection	1 pc.	100%	Visual Aid	If wires oriented wrong (wrong hole or crossed), disassemble and reassemble.

Exhibit G. Process Potential Failure Mode and Effects Analysis {abridged}

Potential Failure Mode and Effect Analysis (Process FMEA)

Modelo / Model #: 25335187, 25335188, 25340321 25340322, 25340323, 25342879 and 25343246

Responsabilidad del Proceso / Process Responsibility: S. Bergman

FMEA #: PROTO_EOS-001

Año Modelo/Vehiculo / Model Year/Vehicle: TBD

Fecha de PPAP / PPAP Date: TBD

FMEA Fecha (Orig.)/ FMEA Date (Orig.): 17-Jul-00

Ultimo Nivel de Cambio / Latest Change Level: 001

Fecha de Rev./Rev. Date: 17-Jul-00

Preparado Por / Prepared by: S. Bergman

Equipo Central / Core Team: Guidance from the Packard Electric Systems PFMEA for the same component

#	Nombre del Proceso / Process Step Name	Función (es) del Proceso / Process Step Function(s)	Modos Potenciales de Falla / Potential Function Failure Modes	Causas Potenciales de Falla / Potential Causes of Failure	Class	Efectos Potenciales de Falla / Potential Effects of Failure	Condiciones Existentes / Existing Conditions: Controles Actuales del Proceso/Current Process Controls					Acciones Correctivas Recomendadas / Recommended Corrective Actions	Responsable de las Acciones Correctivas y Fecha de Cumplimiento / Responsible for Corrective Actions & Target Completion Date	Resultados / Resulting: Acciones Correctivas Tomadas / Corrective Actions Taken				
10	Wire Cut	Lead preparation -Cut Cable to Length	Incorrect Cable Length--Short	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness		3	2	6	36							
						EXTERNAL Difficulty Connecting Harness Adapter to Sensor Mating Part and Harness Connector to Vehicle Mating Part		3	6	6	108							
			Incorrect Cable Length--Long	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Interference Induced Damage to Cable ***Short Circuit Failure***		3	9	6	162							
			Decreased Integrity of Core Strands	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Reduced Sensor Life		3	9	6	162							
			Cut Core Strands	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Broken Terminal Connection ***Scrap***		3	4	4	48							
						EXTERNAL Reduced Sensor Life		3	9	4	108							
			Fissures in Insulation	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Water Intrusion ***Short Circuit Failure***		3	9	6	162							
			Incorrect Cable	Failure to Pick Proper Components From Inventory		INTERNAL Inability to Assemble the Harness ***Scrap***		3	9	6	162							
						EXTERNAL Water Intrusion, Melted Insulation or Reduced Structural Stability ***Short Circuit Failure***		3	9	6	162							

Exhibit H. Process Flow Plan {abridged}

Process Flow Diagram

No. Modelo/Model#: 25335187 25335188 25340321 25340322 25340323 25342879 25343246	Responsabilidade do Processo/ Process Responsibility: **S. Bergman**	PFD#: **PROTO_EOS-001**
Ultimo Nivel de Revisão/ Latest Change Level: **Rev. 01**		
Modelo Ano/Veículo)/ Model Year/Vehicle (s): **TBD**	PPAP Data/ PPAP Date: **TBD**	Preparado Por/Prepared By: **S. Bergman**
	Data (Original)/ Date (Original):	Data da Revisão/ Date (Revised): **07/17/00**
Equipe Principal/ Core Team:		

NO. da Operação/ Descricao/Operation Number/ Brief Description	Fontes de Variação/ Incoming Source of Variation	Diagrama de Fluxo de Processo/Process Flow Diagram	Característica do Produto/Product Characteristics	Característica do Processo/Process Characteristics
70 **Terminal Weld**	Bad Terminal Crimp	70	100% Pooled Weld Zone	Check Weld Zone for Proper Pool Using Microscope
80 **Terminal Seat**	Bad Terminal Crimp	80	Terminals Fully Engaged in Ceramics	Visual Inspection
	Bad Terminal Weld Wrong or Damaged Terminal		Proper Terminal Geometry	Visual Inspection
90 **Electrical Test**	Wires Not Properly Oriented	90	Wires Properly Oriented For 25335187, 25335188 and 25343246: Cavity 1--Purple Cavity 2--White Cavity 3--Gray Cavity 4--Black For 25340321, 25340322 and 25340323: Cavity A--Purple Cavity B--White Cavity C--Black Cavity D--Gray For 25342879: Cavity A--Gray Cavity B--Black Cavity C--White Cavity D--Purple	Electrical Continuity Test Using Harness Tester
	Components Missing or Damaged		Each Wire in the Proper Seal Hole and the Proper Ceramic Terminal Lock Hole	Electrical Continuity Test Using Harness Tester

Exhibit I. English Sample Build Operator Instructions

DELPHI

Automotive Systems

INSTRUCCIONES DE ENSAMBLE

NUMERO DE MODELO: **25335187, 25335188, 25340321, 25340322, 25340323, 25342879 and 25343246**

I. NOMBRE DE LA OPERACION Y NUMERO:

1).- Operation 40 -- Manually cut and attach sleeve

II. MATERIAL:

1).- MS010018 -- Sleeve

2).-

3).-

4).-

5).-

III. EQUIPO / HERRAMIENTAS

1).- Wire cutters or scissors

2).- Metric measuring scale

3).-

4).-

IV. SET UP

1).- Move sleeve material spool to work area

2).- Prepare measuring device for 300 mm. to 600 mm.

3).- Prepare hand wire cutters or scissors to cut 2 mm. thick acrylic

V. OBJETIVO

1).- Manually cut the protective sleeve and attach it to the assembly

VI. PROCEDIMIENTO DE OPERACION:

1).- Cut a piece of the sleeve material to the proper length for the model number

Sleeves

Model	Length
25335187	420
25335188	565
25340321	240
25340322	290
25340323	360
25342879	330
25343246	340

*All lengths in mm.
*All Lengths +/- 10.0 mm.

2).- Feed all wires through the sleeve

3).- Push the sleeve back against the connector to allow for further assembly

4).- Safety: Follow all site safety rules and guidelines

5).- Safety: Safety glasses must be worn at all times

6).-

7).-

8).-

9).-

10).-

VII. PUNTOS DE CALIDAD

1).- After cutting the sleeve, measure it to verify it is the proper length

2).-

3).-

" CADA PERSONA ES RESPONSIBLE POR SU PROPIA CALIDAD"

EQUIPO DE REVISION

FECHA DE REVISION: ____________

1.- RESPONSABLE DE ENSAMBLE

2.- INGENIERO REQUISITOR

Exhibit J. Spanish Sample Build Operator Instructions

DELPHI

Automotive Systems

INSTRUCCIONES DE ENSAMBLE

NUMERO DE MODELO: 25335187, 25335188, 25340321, 25340322, 25340323, 25342879 and 25343246

I. NOMBRE DE LA OPERACION Y NUMERO:

1).- Operation 40 – Corte y ensamble manualmente la funda

II. MATERIAL:

1).- MS010018 -- Funda

2).-

3).-

4).-

5).-

III. EQUIPO / HERRAMIENTAS

1).- Alicates de corte o tijeras

2).- Escala métrico

3).-

4).-

IV. SET UP

1).- Mueva funda material a la mesa de trabajo

2).- Prepare escala para 300 mm. a 600 mm.

3).- Prepare alicates de corte o tijeras cortar acrílico de 2 mm. de espesor

V. OBJETIVO

1).- Corte y ensamble manualmente la funda a la guarniciones del alambre

VI. PROCEDIMIENTO DE OPERACION:

1).- Corte un piece de la funda material a la dimension apropriado para el numero de modelo

Sleeves

Modelo	Longitude
25335187	420
25335188	565
25340321	240
25340322	290
25340323	360
25342879	330
25343246	340

*Todas longitudes en mm.
*Todas longitudes +/- 10.0 mm.

2).- Tire los alambres a través de la funda

3).- Empuje de la funda contra el conector dejar sitio para más asamblea

4).- Seguridad: Siga todas las reglas y las pautas de seguridad de sitio

5).- Seguridad: Deben llevarse las gafases de seguridad en todo momento

6).-

7).-

8).-

9).-

10).-

VII. PUNTOS DE CALIDAD

1).- Después corte la funda, meda verificar la longitud es aproriado

2).-

3).-

" CADA PERSONA ES RESPONSIBLE POR SU PROPIA CALIDAD"

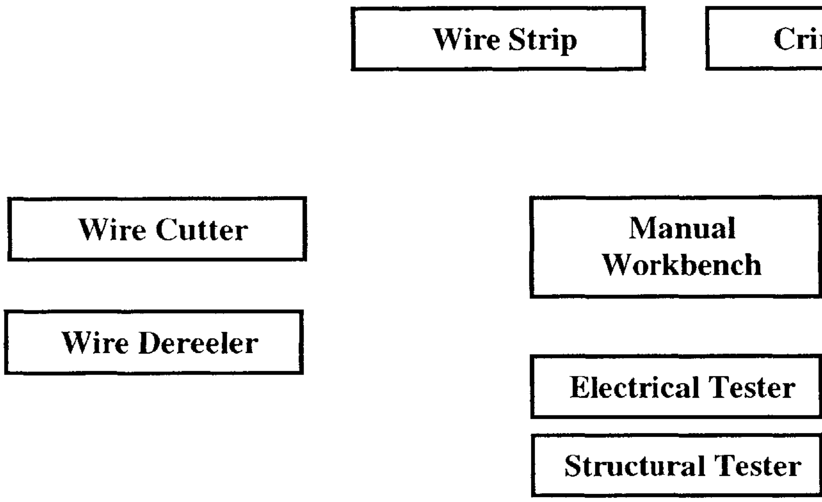
EQUIPO DE REVISION

FECHA DE REVISION: ____________________

1.- RESPONSABLE DE ENSAMBLE

2.- INGENIERO REQUISITOR

Exhibit K. Recommended Flexible Harness Prototype System



Appendix B

The Benchmarking Study

The Benchmarking Study

Methodology

Conducting a benchmarking study with a broad range of products and production systems presents the greatest chance that best practices will be determined. In order to broaden the range of data included in the study, several harness varieties and numerous information sources were utilized.

- Baseline exhaust oxygen sensor harness from the Energy and Chassis system division
- In-the-market exhaust oxygen sensor harness from the Packard Electric Systems division
- Next generation exhaust oxygen sensor harness from the Packard Electric Systems division
- Competitive exhaust oxygen sensor harness from Bosch
- Competitive exhaust oxygen sensor harness from Nippendenso
- Competitive exhaust oxygen sensor harness from NTK
- Non-exhaust oxygen sensor harness from the Energy and Chassis system division
- Industry data from United States Council for Automotive Research (USCAR)
- Industry data from Society of Automotive Engineers (SAE)
- Standards data from Wire Harness Manufacturers Association (WHMA)
- Standards data from Institute of Electrical and Electronics Engineers (IEEE)
- Standards data from National Electrical Manufacturers Association (NEMA)
- Standards data from American Society for Testing and Materials (ASTM)

The baseline for the benchmarking study was the current products and production systems in place within the Energy and Chassis Systems division. The standards and best practices already institutionalized within the industry were added to the baseline as a starting point for the analyses.

Operational evaluation and tear down was the comparative analysis plan for the benchmarking study. Differences in exhaust oxygen sensors made operation evaluation prohibitive. Tear down comparative analysis was conducted on seven harnesses, six exhaust oxygen sensor harnesses and one other sensor harness.

The data obtained from the comparative analysis was discussed with technical experts within the Energy and Chassis Systems division. These experts acted as a filter to determine which of the studies findings could be considered current lessons learned and which of study findings needed further research before being institutionalized within the organization.

Baseline

The baseline for the benchmarking study was the current products and production systems in place within the Energy and Chassis Systems division. Using the Systems Failure Method[41] framework,

[41] Fortune, Joyce, and Geoff Peters. Learning from Failure -- The Systems Approach. New York: John Wiley & Sons, 1995.: p. 247.

the baseline description was supplemented to focus the comparative analysis on product features and production processes requiring potential improvements.

- Definition of the System
  - The system is the exhaust oxygen sensor harness. It is comprised of a vehicle connector, a signal transfer system and a sensor connector.

- Description of System Operation
  - The exhaust oxygen sensor harness connects the exhaust oxygen sensor to the on-board computer and the electrical system in the vehicle. This connection allows electrical signals to be interchanged.

- Description of the Environmental Conditions
  - The exhaust oxygen sensor harness must withstand temperatures near 900° C. The harness must be able to withstand immersion in oil, automotive fluids and salt water. It must also be able to withstand impact from gravel and road debris.

- Failure Detection
  - The Energy and Chassis Systems division's warranty information and Packard Electric Systems division potential failure modes and effects analyses were used to determine major system failures. The information was based on long-term customer feedback.

- Analysis of Failure Mechanisms
  - Failure detection data confirm that the chief failure mechanisms occur at the connections between the vehicle and sensor connectors and the signal transfer system. An additional failure mechanism occurs with structural failures in the signal transfer system.

- Analysis of Failure Effects
  - The exhaust oxygen sensor harness is an integral part of the exhaust oxygen sensor. Failures in the harness cause a lack of functionality in the entire sensor. A vehicle will continue to operate with a nonfunctioning sensor. However, this operation will be at an increased level of emissions and reduced level of fuel efficiency.

- Compensation for Failure
  - In the vehicle system, the compensation for failure is a signal of the failure through a 'check engine' light illuminating. Further compensation for failure can be facilitated through corrective actions developed from the lessons learned in the benchmarking study.

Comparative Analysis

Operational evaluation of the competitive products followed by tear down analysis was the initial comparative analysis plan for the benchmarking study. However, differences in the exhaust oxygen sensors precluded the operational evaluation. Only tear down analysis was completed.

The products were torn down so that the harnesses were isolated from the sensors. Material types and processes utilized were determined. The best material and process combinations observed in the benchmarking study were then selected from this information. A tabulation of some of the study's findings is contained in *Table I*, *Table II* and *Table III*.

Table I. Benchmarking Study Results--Vehicle Connection System

Vehicle Connection System Benchmarking

HARNESS	FEATURE: Vehicle Connector
Baseline	Purchased, Three pieces--connector, terminal position assurance, clip
Packard Electric Systems--In-the-market	Purchased, Three pieces--connector, terminal position assurance, clip
Packard Electric Systems--Next generation	Purchased, Three pieces--connector, terminal position assurance, clip
Bosch	Molded, Two pieces--clip
Nippendenso	Purchased, Three pieces--connector, terminal position assurance, clip
NTK	Purchased, Three pieces--connector, terminal position assurance, clip
Energy and Chassis Systems--Non-EOS Harness	Molded, One piece--no clip
Industry Standards	WHMA/SAE Some form of terminal position assurance

HARNESS	FEATURE: Vehicle Connector Terminals
Baseline	Connector Specific, Snap-In
Packard Electric Systems--In-the-market	Connector Specific, Snap-In
Packard Electric Systems--Next generation	Connector Specific, Snap-In
Bosch	Generic--Overmolded
Nippendenso	Connector Specific, Snap-In
NTK	Connector Specific, Snap-In
Energy and Chassis Systems--Non-EOS Harness	Generic--Overmolded
Industry Standards	USCAR/SAE Move to Generic--Overmolded

Table II. Benchmarking Study Results--Signal Transfer System

Signal Transfer System Benchmarking

HARNESS	FEATURE: Environmental Protection Device
Baseline	Coated sleeve
Packard Electric Systems--In-the-market	Coated sleeve
Packard Electric Systems--Next generation	Plastic coated sleeve
Bosch	Plastic coated sleeve
Nippendenso	Insulation covering the wire set
NTK	Plastic coated sleeve
Energy and Chassis Systems--Non-EOS Harness	Insulation covering the wire set
Industry Standards	IEEE/ASTM/NEMA/WHMA Some form of environmental protection

Table III. Benchmarking Study Results--Sensor Connection System

Sensor Connection System Benchmarking

HARNESS	FEATURE: Insulating Ceramic Components
Baseline	One component
Packard Electric Systems--In-the-market	Several components
Packard Electric Systems--Next generation	Several components
Bosch	One component with integrated seals
Nippendenso	Several components
NTK	One component
Energy and Chassis Systems--Non-EOS Harness	Overmolded Sensor
Industry Standards	Not Applicable

HARNESS	FEATURE: Structural Metallic Components
Baseline	One component
Packard Electric Systems--In-the-market	One component
Packard Electric Systems--Next generation	Several components--Two metallic, Breathability components
Bosch	Several components--Two dissimilar metallic
Nippendenso	Several components--Two dissimilar metallic, Breathability components
NTK	One component
Energy and Chassis Systems--Non-EOS Harness	Overmolded Sensor
Industry Standards	Not Applicable

HARNESS	FEATURE: Sealing Components
Baseline	Elastomer Plug Seal
Packard Electric Systems--In-the-market	Elastomer Plug Seal
Packard Electric Systems--Next generation	Elastomer Plug Seal
Bosch	Integrating into the insulating ceramic components
Nippendenso	Elastomer Plug Seal
NTK	Elastomer Plug Seal
Energy and Chassis Systems--Non-EOS Harness	O-Ring Seals
Industry Standards	Not Applicable

HARNESS	FEATURE: Sensor Connector Terminals
Baseline	Crimp and Plasma Welded
Packard Electric Systems--In-the-market	Crimp and Laser Welded
Packard Electric Systems--Next generation	Crimp and Laser Welded
Bosch	Crimp Only
Nippendenso	Crimp and Resistance or Laser Welded
NTK	Crimp and Resistance or Laser Welded Specific Terminals
Energy and Chassis Systems--Non-EOS Harness	Not Applicable
Industry Standards	Not Applicable

Results

The combination of exhaust oxygen sensor harnesses, non-exhaust oxygen sensor harness and industry standards provided a broad range of product design and process technology concepts. Despite the limited differences in the benchmarking study population, potential best practices were determined for each of the three harness sub-blocks.

The potential best practices were discussed with experts within the Energy and Chassis Systems division. The ultimate result of the benchmarking study was a set of action plans for further investigation. When these action plans are completed, successful research conclusions can be incorporated into product design and process selection through inclusion in the best practices repository. A tabulation of the final study conclusions is contained in *Table IV*, *Table V* and *Table VI*.

Table IV. Benchmarking Study Conclusions--Vehicle Connection System

Vehicle Connection System Benchmarking	
FEATURE: Vehicle Connector	**FEATURE: Vehicle Connector Terminals**
Conclusion:	**Conclusion:**
Investigate overmolding designs and processes	Investigate generic terminals as part of overmolding design and process
Rationale:	**Rationale:**
Reduce component costs Ability to design connectors with exact features required Ability to eliminate sealing components in weathertight designs Ability to build competencies for processing embedded circuitry Ability to utilize generic terminals	Reduce component costs
Action Plan:	**Action Plan:**
Build harnesses using already developed overmolded connectors Develop harness specific overmolded connector and generic terminals Build prototypes using harness specific overmolding components Develop business case if investigation garners positive results	Follow Investigate overmolding designs and processes Action Plan
Issues:	**Issues:**
Switching costs Ability to design in all features without molding complexity	Switching costs
Benchmark Study Examples:	**Benchmark Study Examples:**
Nippendenso Energy and Chassis Systems--Non-EOS Harness	Nippendenso Energy and Chassis Systems--Non-EOS Harness

Table V. Benchmarking Study Conclusions--Signal Transfer System

Signal Transfer System Benchmarking
FEATURE: Environmental Protection Device
Conclusion:
Investigate using complete insulation coverage of the wire set
Rationale:
Reduce process steps
Ability to fully cover wires to protect against environmental damage
Action Plan:
Build harnesses using insulation covered wire set
Complete battery of engineering change tests on harnesses
Develop business case if investigation garners positive results
Issues:
Cost tradeoff between material and process changes
Ability to visual verify proper wiring during assembly
Ability to design in strain relief features
Benchmark Study Examples:
Nippendenso
Energy and Chassis Systems--Non-EOS Harness

Table VI. Benchmarking Study Conclusions--Sensor Connection System

Sensor Connection System Benchmarking
FEATURE: Sensor Connector Terminals
Conclusion:
Investigate elimination of termination welds
If elimination investigation fails, investigate different termination technologies
Rationale:
Elimination: reduce process steps
Investigation of technologies: find common technology to proliferate globally to reduce structural costs
Action Plan:
Improve crimp process quality assurance capabilities
Build harnesses using only terminal crimp
Complete battery of engineering change tests on harnesses
If investigation garners positive results, develop business case
If investigation does not produce positive results, investigate termination technologies
Build harnesses using laser, resistance and plasma weld technologies
Complete battery of engineering change tests on harnesses and conduct comparative analysis
Determine best process technology based on product quality and process cost
Develop business case for adoption of one termination technology
Issues:
Cost tradeoff between process changes and potential warranty issues
Ability to design using materials acceptable to one termination technology
Benchmark Study Examples:
Bosch
NTK

Lessons from the benchmarking study produced insights regarding future trends in the industry. These trends need further investigation before incorporation into the exhaust oxygen sensor harness product and processes.

Product design and process technology experimentation is essential to understanding the technological direction of the industry. This understanding is vital to building the product and process competencies necessary to effectively compete in the market as the technologies become customer requirements.

Appendix C

Bill of Process

Bill of Process

Bill of Process

In the Energy and Chassis Systems division, the bill of process signifies an initiative to identify and document the best manufacturing processes and process sequences for each product family. The initiative's goal is to determine the best manufacturing systems that can be standardized globally to provide the division with a competitive advantage.

Information obtained from the prototype system and the benchmarking study was used to develop a bill of process for a family of exhaust oxygen sensor harnesses. A portion of the created bill of process for the planar family of exhaust oxygen sensor harnesses follows.

Delphi Energy and Chassis Systems
Bill of Process

Exhaust Oxygen Sensor
Wire Harness
{Planar Family}

Delphi Automotive Systems

Bill of Process
Owner

____

Release Date: ______________

Table of Contents

Bill of Process Document Release

Product Design Variants Included:	Exhaust Oxygen Sensor Harness Planar Family 25335187 25335188 25340321 25340322 25340323 25342879 25343246
Product Design Variants Excluded:	Exhaust Oxygen Sensor Harness Stoichiometric Family Standard Family Wide Range Family
Core Team Members/Location:	Delphi Energy and Chassis Systems Mexico Technical Center
Manufacturing Sites Affected:	Delphi Energy and Engine Management Systems

Approvals

BOP Owner/date: ______________________________

Chief Engineer, Mfg. Eng./date: ______________________________

Staff Engineer/date: ______________________________

Release Date: ______________________________

A bill of process describes the "best practice" for making a product. A "best practice" is defined as the most efficient manufacturing method and is not an indication of variations in product quality or performance.

Revision History

Release Date: ____________________ **Change Control No.** ____________________
Revision: ____________________

Purpose: ____________________

Approvals

BOP Owner/date: ____________________
Chief Engineer, Mfg. Eng./date: ____________________
Staff Engineer/date: ____________________

Release Date: ____________________ **Change Control No.** ____________________
Revision: ____________________

Purpose: ____________________

Approvals

BOP Owner/date: ____________________
Chief Engineer, Mfg. Eng./date: ____________________
Staff Engineer/date: ____________________

Release Date: ____________________ **Change Control No.** ____________________
Revision: ____________________

Purpose: ____________________

Approvals

BOP Owner/date: ____________________
Chief Engineer, Mfg. Eng./date: ____________________
Staff Engineer/date: ____________________

Scope

The Exhaust Oxygen Sensor

The exhaust oxygen sensor is used in vehicles with internal combustion engines that use closed-loop control schemes to meet emissions regulations and to achieve fuel efficiency requirements. Most vehicles currently produced have two exhaust oxygen sensors in each exhaust pipe.

The control sensor, located between the engine and the catalytic converter, feeds the on-board computer exhaust information that allows the system to adjust to release the lowest possible emissions. The post-converter sensor, located after the catalytic converter, is used to assure that the converter is functioning appropriately in order to meet onboard diagnostics standards.

There are four families of exhaust oxygen sensors.

1. Stoichiometric
2. Standard
3. Planar
4. Wide Range

This bill of process will focus solely on the planar family of exhaust oxygen sensor harnesses.

The Exhaust Oxygen Sensor Harness

The purpose of a sensor harness is to connect the sensor to the on-board computer and the electrical system in the vehicle to allow electrical signals to be interchanged. These signals include sensor power, sensor ground and sensor output.

The harness is comprised of three system sub-blocks in order to complete these functions.

1. The vehicle connection system
2. The signal transfer system
3. The sensor connection system

In the planar family of oxygen sensor harnesses, the vehicle connection system contains a plastic connector and electrical terminals. The signal transfer system contains a protective sleeve and four wires. These wires are terminated at one end with the vehicle connection system electrical terminals. On the other end, the wires are terminated with the sensor connection system electrical terminals. The sensor connections system contains a ceramic insulating component, a metal structural component, a weathertight seal and electrical terminals.

The exhaust oxygen sensor is mounted in the engine exhaust stream. This causes the product's subassemblies to have strict structural requirements. Temperature is a particularly important issue as exhaust temperature can increase to over 900° C. The harness is not directly subjected to these temperature extremes. However, it does have strict electrical, mechanical, temperature and environmental requirements. A subset of these requirements is listed below.

- Electrical Requirements
  - Operating Voltage
  - Output Voltage
  - Source Current
  - Sink Current
  - Lead Termination Resistance
  - Signal Lead Resistance
  - Power Lead Resistance
  - Insulation Resistance
  - Lead Continuity

- Mechanical Requirements
  - Lead Termination Tensile Strength
  - Lead Termination to Connector Retention Force
  - Vehicle Connector Mating Force
  - Vehicle Connector Retention Force
  - Vehicle Connector Disengage Force

- Temperature Requirements
  - Low Temperature Operation
  - High Temperature Operation
  - High Temperature Stability

- Environmental Requirements
  - Structure Breathability
  - Withstand Immersion in Oil
  - Withstand Immersion in Automotive Fluids and Coolants
  - Withstand Immersion in Salt Water
  - Withstand Impact by Gravel

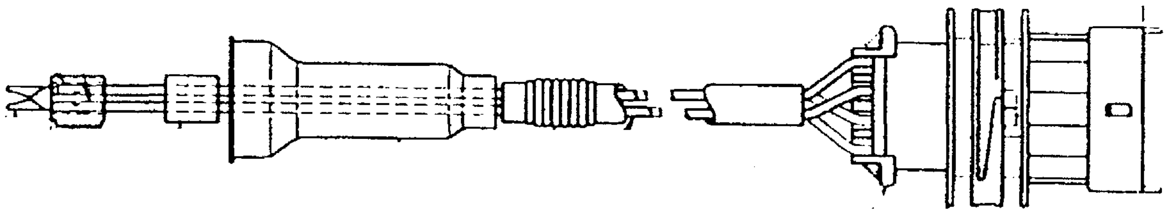
Bill of Materials

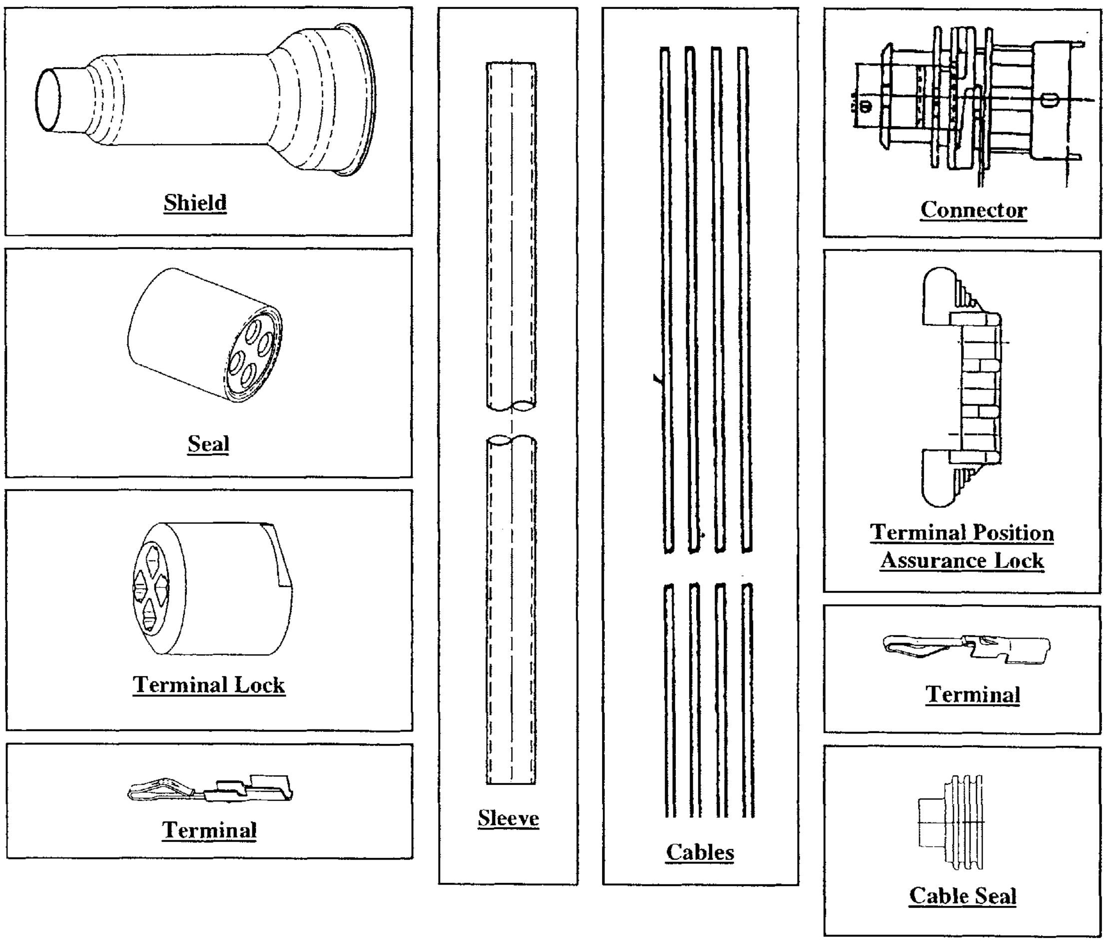
Connector Assembly
- Connector
- Terminal Position Assurance Lock {when applicable}
- (4) Terminal
- (4) Cable Seal

Sleeve
(4) Cable
Shield
Seal
Terminal Lock
(4) Terminal

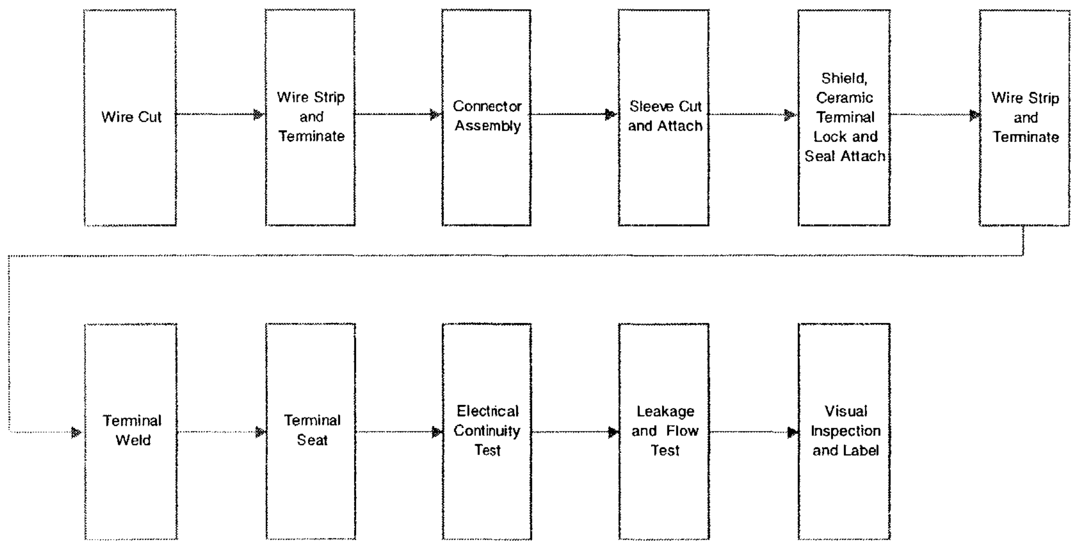
Delphi Energy and Chassis Systems – Bills of Process are **UNCONTROLLED DOCUMENTS FOR REFERENCE ONLY**

Product Terminology Diagram





Manufacturing Sequence Diagram



Process Flow Diagram

Process Flow Diagram

No. Modelo/Model #: 25335187 25335188 25340321 25340322 25340323 25342879 25343246	Responsabilidade do Processo/ Process Responsibility: **S. Bergman**	PFD#: **F-EOSP-HARNESS-001**
Modelo Ano/Veículo)/ Model Year/Vehicle (s): **TBD**	PPAP Data/ PPAP Date: **TBD**	Ultimo Nivel de Revisão/ Latest Change Level: **Rev. 01** Preparado Por/Prepared By: **S. Bergman**
	Data (Original)/ Date (Original): **07/17/00**	Data da Revisão/ Date (Revised): **07/17/00**
Equipe Principal/ Core Team:		

NO. da Operação/ Descricao/Operation Number/ Brief Description	Fontes de Variação/ Incoming Source of Variation	Diagrama de Fluxo de Processo/Process Flow Diagram	Característica do Produto/Product Characteristics	Característica do Processo/Process Characteristics
00 **Receiving Inspection**	Geometric Dimensions Variation Material Variation Shipping Material Handling Damage	00		
Shield Terminal Ceramic Terminal Lock			KPC	
10 **Wire Cut**	Deformations In Wire Insulation	10	No Process Induced Deformations in Insulation	Visual Inspection
Cable EQUIPMENT Wire Dereeler Wire Cutter	Wrong Wire Type or Gage		Proper Wire Length	Inspection of Wire Length Using Metric Graduated Ruler or Equivalent
20 **Wire Strip and Terminate**	Deformations In Wire or Wire Insulation	20	No Process Induced Deformations in Insulation	Visual Inspection
Terminal *Cable Seal* EQUIPMENT Wire Stripper Crimp Press	Wrong or Damaged Seal Wrong or Damaged Terminal		All Components Present and Properly Oriented	Visual Inspection

Process Flow Diagram

No. Modelo/Model #: 25335187 25335188 25340321 25340322 25340323 25342879 25343246	Responsabilidade do Processo/ Process Responsibility: **S. Bergman**	PFD#: **F-EOSP-HARNESS-001**
Modelo Ano/Veículo)/ Model Year/Vehicle (s): **TBD**	PPAP Data/ PPAP Date: **TBD**	Ultimo Nivel de Revisão/ Latest Change Level: **Rev. 01** Preparado Por/Prepared By: **S. Bergman**
Equipe Principal/ Core Team:	Data (Original)/ Date (Original): **07/17/00**	Data da Revisão/ Date (Revised): **07/17/00**

NO. da Operação/ Descricao/Operation Number/ Brief Description	**Fontes de Variação/ Incoming Source of Variation**	**Diagrama de Fluxo de Processo/Process Flow Diagram**	**Característica do Produto/Product Characteristics**	**Característica do Processo/Process Characteristics**
30 **Connector Assembly** *Connector* *TPA Lock*	Deformations In Wire Insulation Wrong or Damaged Seal Wrong or Damaged Terminal Wrong or Damaged Connector Assembly Wrong or Damaged Terminal Position Assurance Lock	30	No Process Induced Deformations in Insulation	Visual Inspection
			All Components Present and Properly Oriented	Visual Inspection
			Wires Properly Oriented in Connector Cavities	Visual Inspection
40 **Sleeve Cut and Attach** *Sleeve*	Wrong or Damaged Sleeve Material	40	Proper Sleeve Length	Inspection of Sleeve Length Using Metric Graduated Ruler or Equivalent

Delphi Energy and Chassis Systems – Bills of Process are **UNCONTROLLED DOCUMENTS FOR REFERENCE ONLY**

Process Flow Diagram

No. Modelo/Model #: 25335187 25335188 25340321 25340322 25340323 25342879 25343246	Responsabilidade do Processo/ Process Responsibility: **S. Bergman**	PFD#: **F-EOSP-HARNESS-001**
		Ultimo Nivel de Revisão/ Latest Change Level: **Rev. 01**
Modelo Ano/Veículo)/ Model Year/Vehicle (s): **TBD**	PPAP Data/ PPAP Date: **TBD**	Preparado Por/Prepared By: **S. Bergman**
	Data (Original)/ Date (Original): **07/17/00**	Data da Revisão/ Date (Revised): **07/17/00**
Equipe Principal/ Core Team:		

NO. da Operação/ Descricao/Operation Number/ Brief Description	Fontes de Variação/ Incoming Source of Variation	Diagrama de Fluxo de Processo/Process Flow Diagram	Característica do Produto/Product Characteristics	Característica do Processo/Process Characteristics
50 **Shield, Ceramic Terminal Lock and Seal Attach**	Wrong or Damaged Shield	50	Each Wire in the Proper Seal Hole and the Proper Ceramic Terminal Lock Hole	Visual Inspection
Shield *Ceramic Terminal Lock* *Seal*	Wrong or Damaged Ceramic Terminal Lock		No Crossed Wires in the Assembly Between the Seal and the Ceramic Terminal Lock	Visual Inspection
	Wrong or Damaged Seal		Proper Shield Orientation	Visual Inspection
			Proper Ceramic Terminal Lock Orientation	Visual Inspection
			Proper Seal Orientation	Visual Inspection
60 **Wire Strip and Terminate**	Deformations In Wire or Wire Insulation	60	Proper Terminal Crimp Dimensions	Set-up of Terminal Crimp Press Pressure
Terminal EQUIPMENT Wire Stripper Crimp Press	Wrong or Damaged Terminal		Proper Crimp Geometry	Verify Geometry to Print Dimensions Using a Microscope
70 **Terminal Weld** EQUIPMENT Welder	Bad Terminal Crimp	70	100% Pooled Weld Zone	Check Weld Zone for Proper Pool Using Microscope

Delphi Energy and Chassis Systems – Bills of Process are **UNCONTROLLED DOCUMENTS FOR REFERENCE ONLY**

Process Flow Diagram

No. Modelo/Model #: 25335187 25335188 25340321 25340322 25340323 25342879 25343246	Responsabilidade do Processo/ Process Responsibility: **S. Bergman**	PFD#: **F-EOSP-HARNESS-001**
Modelo Ano/Veiculo)/ Model Year/Vehicle (s): **TBD**	PPAP Data/ PPAP Date: **TBD**	Ultimo Nivel de Revisão/ Latest Change Level: **Rev. 01** Preparado Por/Prepared By: **S. Bergman**
Equipe Principal/ Core Team:	Data (Original)/ Date (Original): **07/17/00**	Data da Revisão/ Date (Revised): **07/17/00**

NO. da Operação/ Descricao/Operation Number/ Brief Description	Fontes de Variação/ Incoming Source of Variation	Diagrama de Fluxo de Processo/Process Flow Diagram	Característica do Produto/Product Characteristics	Característica do Processo/Process Characteristics
80 **Terminal Seat**	Bad Terminal Crimp	80	Terminals Fully Engaged in Ceramic Terminal Lock	Visual Inspection
	Bad Terminal Weld Wrong or Damaged Terminal		Proper Terminal Geometry	Visual Inspection
90 **Electrical Test**	Wires Not Properly Oriented		Wires Properly Oriented	Electrical Test
EQUIPMENT Electrical Tester	Components Missing or Damaged	90	Each Wire in the Proper Seal Hole and the Proper Ceramic Terminal Lock Hole	Electrical Test
100 **Leakage and Flow Test** EQUIPMENT Tester	Deformations In Wire Insulation	100	Allowable Leakage Required Breathability	Tester
110 **100% Visual Inspection and Mark**	Deformations In Wire Insulation	110	Terminals Fully Engaged in Ceramic Terminal Lock	Visual Inspection
	Wires Not Properly Oriented		Proper Terminal Geometry	Visual Inspection
	Components Missing or Damaged		All Components Present and Properly Oriented	Visual Inspection

Delphi Energy and Chassis Systems – Bills of Process are **UNCONTROLLED DOCUMENTS FOR REFERENCE ONLY**

Potential Failure Mode and Effect Analysis

Potential Failure Mode and Effect Analysis (Process FMEA)

Modelo / Model #: 25335187, 25335188, 25340321, 25340322, 25340323, 25342879 and 25343246

Responsabilidad del Proceso/ Process Responsibility: S. Bergman

FMEA #: F-EOSP-HARNESS-001

Año Modelo/Vehículo / Model Year/Vehicle: TBD

FMEA Fecha (Orig.)/ FMEA Date (Orig.): 17-Jul-00

Fecha de PPAP/ PPAP Date: TBD

Ultimo Nivel de Cambio / Latest Change Level: 001

Fecha de Rev./ Rev. Date: 17-Jul-00

Preparado Por/ Prepared by: S. Bergman

Equipo Central / Core Team: Guidance from the Packard Electric Systems PFMEA for the same component

#	Nombre del Proceso / Process Step Name	Función (es) del Proceso / Process Step Function(s)	Modos Potenciales de Falla / Potential Function Failure Modes	Causas Potenciales de Falla / Potential Causes of Failure	Class	Efectos Potenciales de Falla / Potential Effects of Failure	Condiciones Existentes/Existing Conditions: Controles Actuales del Proceso/Current Process Controls	Occ	Sev	Det	RPN	Acciones Correctivas Recomendadas / Recommended Corrective Actions	Responsable de las Acciones Correctivas y Fecha de Cumplimiento / Responsible for Corrective Actions & Target Completion Date	Resultados/Resulting: Acciones Correctivas Tomadas/ Corrective Actions Taken	Occ	Sev	Det	RPN
10	Wire Cut	Lead preparation -Cut Cable to Length	Incorrect Cable Length--Short	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
						EXTERNAL Difficulty Connecting Harness Adapter to Sensor Mating Part and Harness Connector to Vehicle Mating Part												
			Incorrect Cable Length--Long	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Interference Induced Damage to Cable ***Short Circuit Failure***												
			Decreased Integrity of Core Strands	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Reduced Sensor Life												
			Cut Core Strands	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Broken Terminal Connection ***Scrap***												
						EXTERNAL Reduced Sensor Life												
			Fissures in Insulation	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Water Intrusion ***Short Circuit Failure***												
			Incorrect Cable	Failure to Pick Proper Components From Inventory		INTERNAL Inability to Assemble the Harness ***Scrap***												
						EXTERNAL Water Intrusion, Melted Insulation or Reduced Structural Stability ***Short Circuit Failure***												
20	Wire Strip and and Terminate	Complete Lead Preparation -Attach Seal -Strip Wire Insulation -Crimp Terminal	Damaged Seal	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Inability to Assemble Connector ***Scrap***												
						EXTERNAL Water Intrusion ***Short Circuit Failure***												
			Missing Seal	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Inability to Assemble Connector ***Scrap***												
						EXTERNAL Water Intrusion ***Short Circuit Failure***												
			Incorrect Seal	Failure to Pick Proper Components From Inventory		INTERNAL Inability to Assemble the Harness ***Scrap***												
						EXTERNAL Water Intrusion or Reduced Structural Stability ***Short Circuit Failure***												
			Decreased Integrity of Core Strands	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Reduced Sensor Life												
			Cut Core Strands	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Broken Crimped Terminal Connection ***Scrap***												
						EXTERNAL Reduced Sensor Life												

Delphi Energy and Chassis Systems – Bill of Process

Exhaust Oxygen Sensor Wire Harness {Planar Family}

Potential Failure Mode and Effect Analysis (Process FMEA)

Modelo / Model #: 25335187, 25335188, 25340321, 25340322, 25340323, 25342879 and 25343246

Responsabilidad del Proceso/ Process Responsibility: S. Bergman

FMEA #: F-EOSP-HARNESS-001

Año Modelo/Vehiculo / Model Year/Vehicle: TBD

FMEA Fecha (Orig.)/ FMEA Date (Orig.): 17-Jul-00

Fecha de PPAP/ PPAP Date: TBD

Ultimo Nivel de Cambio / Latest Change Level: 001

Fecha de Rev./ Rev. Date: 17-Jul-00

Preparado Por/ Prepared by: S. Bergman

Equipo Central / Core Team: Guidance from the Packard Electric Systems PFMEA for the same component

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			Partial or Incomplete Insulation Strip	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Bad Crimped Terminal Connection ***Scrap***												
						EXTERNAL Intermittent or Poor Signal												
			Long Insulation Strip	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Reduced Sensor Life due to exposed strands, leakage or core oxidation												
						EXTERNAL ***Short Circuit Failure***												
			Insulation Under Crimp	Incorrect Strip Set-up, Failure to Follow Instructions; Incorrect Crimp Set-up, Failure to Follow Instructions		INTERNAL Bad Crimped Terminal Connection ***Scrap***												
						EXTERNAL Intermittent or Poor Signal												
						EXTERNAL Reduced Sensor Life												
			Missing Terminal	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
						EXTERNAL Intermittent or Poor Signal												
						EXTERNAL Reduced Sensor Life												
						EXTERNAL Difficulty Connecting Harness Adapter to Sensor Mating Part and Harness Connector to Vehicle Mating Part												
			Damaged Terminal	Incorrect Material Handling, Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
						EXTERNAL Intermittent or Poor Signal												
						EXTERNAL Reduced Sensor Life												
						EXTERNAL Difficulty Connecting Harness Adapter to Sensor Mating Part and Harness Connector to Vehicle Mating Part												
			Core Strands Outside of Crimp	Incorrect Crimp Set-up, Failure to Follow Instructions; Incorrect Crimp Pressure; Worn Crimp Tool		INTERNAL Difficulty Assembling the Harness												
						EXTERNAL Intermittent or Poor Signal												
						EXTERNAL Reduced Sensor Life												
			No Crimp Flare	Incorrect Crimp Set-up, Failure to Follow Instructions; Incorrect Crimp Pressure; Worn Crimp Tool		INTERNAL Difficulty Assembling the Harness												
						EXTERNAL Intermittent or Poor Signal												
						EXTERNAL												

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Preparado Por/ Prepared by: S. Bergman

Equipo Central / Core Team: Guidance from the Packard Electric Systems PFMEA for the same component

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			Incomplete Crimp	Incorrect Crimp Set-up, Failure to Follow Instructions Incorrect Crimp Pressure Worn Crimp Tool		INTERNAL Difficulty Assembling the Harness												
						EXTERNAL Intermittent or Poor Signal												
						EXTERNAL Reduced Sensor Life												
			Incorrect Crimp Dimensions	Incorrect Crimp Set-up, Failure to Follow Instructions Incorrect Crimp Pressure Worn Crimp Tool		INTERNAL Difficulty Assembling the Harness												
						EXTERNAL Intermittent or Poor Signal												
						EXTERNAL Reduced Sensor Life												
30	Connector Assembly	Build Subassembly of Connector and Leads -Plug Terminated Wires into Connector -Assemble Terminal Position Assurance Lock	Terminated Wires Plugged into Incorrect Cavity	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Failure at Electrical Continuity Test ***Scrap***												
						EXTERNAL Sensor Inoperable												
			Missing Terminal Position Assurance Lock and Not Fully Seated Terminals	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Intermittent or Poor Signal												
						EXTERNAL Reduced Sensor Life												
			Incorrect Terminals	Failure to Pick Proper Components From Inventory		INTERNAL Inability to Assemble the Harness ***Scrap***												
						INTERNAL Failure at Electrical Continuity Test ***Scrap***												
						EXTERNAL Water Intrusion, Melted Insulation or Reduced Structural Stability ***Short Circuit Failure***												
						EXTERNAL Difficulty Connecting Harness Adapter to Sensor Mating Part and Harness Connector to Vehicle Mating Part												
40	Sleeve Cut and Attach	Attach Sleeve to the Assembly -Cut Sleeve Material to Size -Slide Sleeve Over Wires -Push Sleeve Back Out of the Way of Further Assembly	Incorrect Cable Length--Short	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
						EXTERNAL Interference Induced Damage to Cable or Melted Insulation ***Short Circuit Failure***												
			Incorrect Cable Length--Long	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
						EXTERNAL Interference Induced Damage to Cable ***Short Circuit Failure***												
50	Shield, Ceramic Terminal Lock and Seal Attach	Attach Shield, Ceramic Terminal Lock and Seal to the Assembly -Feed Wires through Shield	Missing Shield	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
			Inverted Shield	Incorrect Set-up, Failure to Follow		INTERNAL Difficulty Assembling												

Potential Failure Mode and Effect Analysis (Process FMEA)

Modelo / Model #: 25335187, 25335188, 25340321, 25340322, 25340323, 25342879 and 25343246

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						EXTERNAL Reduced Sensor Life												
			Feed Wires Incorrectly through Seal	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
						INTERNAL Failure at Electrical Continuity Test ***Scrap***												
						EXTERNAL Oxygen Sensor Time To Activity Test or Audit Test Failure												
						EXTERNAL Sensor Inoperable												
			Fissures in Insulation	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Water Intrusion ***Short Circuit Failure***												
			Missing Ceramic Terminal Lock	Incorrect Set-up Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
			Inverted Ceramic Terminal Lock	Incorrect Set-up Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
60	Wire Strip and Terminate	Complete Leads -Strip Wire Insulation -Crimp Terminal	Missing Terminal	Incorrect Set-up, Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
						EXTERNAL Intermittent or Poor Signal												
						EXTERNAL Reduced Sensor Life												
						EXTERNAL Sensor Inoperable												
			Incorrect Terminals	Failure to Pick Proper Components From Inventory		INTERNAL Inability to Assemble the Harness ***Scrap***												
						INTERNAL Failure at Electrical Continuity Test ***Scrap***												
						EXTERNAL Reduced Structural Stability ***Short Circuit Failure***												
						EXTERNAL Difficulty Connecting Harness Adapter to Sensor Mating Part												
			Insulation Under Crimp	Incorrect Strip Set-up, Failure to Follow Instructions Incorrect Crimp Set-up, Failure to Follow Instructions		INTERNAL Bad Crimped Terminal Connection ***Scrap***												
						EXTERNAL Intermittent or Poor Signal												
						EXTERNAL Reduced Sensor Life												
			Core Strands Outside of Crimp	Incorrect Crimp Set-up, Failure to Follow Instructions		INTERNAL Difficulty Assembling the Harness												
				Incorrect Crimp Pressure		EXTERNAL Intermittent or Poor Signal												

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			Incomplete Crimp	Incorrect Crimp Set-up, Failure to Follow Instructions Incorrect Crimp Pressure Worn Crimp Tool		INTERNAL Difficulty Assembling the Harness EXTERNAL Intermittent or Poor Signal EXTERNAL Reduced Sensor Life												
			Incorrect Crimp Dimensions	Incorrect Crimp Set-up, Failure to Follow Instructions Incorrect Crimp Pressure Worn Crimp Tool		INTERNAL Difficulty Assembling the Harness EXTERNAL Intermittent or Poor Signal EXTERNAL Reduced Sensor Life												
			Damaged Terminal	Incorrect Crimp Set-up, Failure to Follow Instructions Incorrect Crimp Pressure Worn Crimp Tool		INTERNAL Difficulty Assembling the Harness EXTERNAL Intermittent or Poor Signal EXTERNAL Reduced Sensor Life EXTERNAL Difficulty Connecting Harness Adapter to Sensor Mating Part												
70	Terminal Weld	Weld Crimped Terminals -Weld Crimped Terminal	Damaged Terminal	Incorrect Material Handling, Failure to Follow Instructions		EXTERNAL Difficulty Connecting Harness Adapter to Sensor Mating Part												
			Bad Weld	Incorrect Set-up, Failure to Follow Instructions Incorrect Weld Parameters		EXTERNAL Intermittent or Poor Signal EXTERNAL Reduced Sensor Life												
			Missing Weld	Incorrect Set-up, Failure to Follow Instructions Skipped Process		EXTERNAL Intermittent or Poor Signal EXTERNAL Reduced Sensor Life												
			Repeated Weld	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Intermittent or Poor Signal EXTERNAL Reduced Sensor Life												
80	Terminal Seat	Seat Terminals into Ceramic Terminal Lock -Seat Terminals in Ceramic Terminal Lock	Damaged Terminal	Incorrect Material Handling, Failure to Follow Instructions		EXTERNAL Difficulty Connecting Harness Adapter to												
			Terminal Not Seated Properly	Incorrect Set-up, Failure to Follow Instructions		EXTERNAL Difficulty Connecting Harness Adapter to Sensor Mating Part												
			Foreign Material Caught Between Terminal and Ceramic Terminal Lock	Incorrect Set-up, Failure to Follow Instructions Incorrect Material Handling, Failure to Follow Instructions		EXTERNAL Difficulty Connecting Harness Adapter to Sensor Mating Part EXTERNAL Intermittent or Poor Signal EXTERNAL Reduced Sensor Life EXTERNAL												

Delphi Energy and Chassis Systems – Bills of Process are **UNCONTROLLED DOCUMENTS FOR REFERENCE ONLY**

Control Plan

Rutina de Proceso: Plan de control de Proceso / Process Routing: Process Control Plan

■ **Prototipo/ Prototype** ☐ **Pre-lanzamiento/ Pre-launch** ☐ **Producción/ Production** **Ultima Rev. de Plano/ Print Rev.:** **Número de Parte/ Part Number: F-EOSP-HARNESS-001**

#Cambio / Chg #	Fecha / Date (rev)	Ing. De Procesos/Herramientas / Process/Tool Engineer	Ingeniero de Calidad / Quality Engineer	Nombre de la Parte/Part Name: Exhaust Oxygen Sensor Harness	Pag./ Page:
		S. Bergman		Nombre del Producto/Product Name: Exhaust Oxygen Sensor	Dept.:
	Fecha / Date (orig)	Aprobación de Ing. Del cliente/Fecha / Cust. Engrg Apvl./ Date (If req'd)	Aprob.calidad del cliente/Fecha/ Cust. Quality. Apvl./Date(if req'd)		
	PCP#			Contacto Clave/Tel/Key Contact/Phone:	
				Planta/Código Prov. / Plant/Supplier Code:	

Equipo Principal / Core Team:

# Op	Descripción de la Operación / Operation Description	Máquina / Machine	Características / Characteristics: No.	Producto / Product	Proceso / Process	Caract. Especial / Special Charact.	Métodos / Methods: Espec. De Prodcuto/Proceso/ Product/Process Specification	Técnicas de Eval./ Medición / Eval./Measurement Technique	Tamaño de Muestra/ Sample Size	Frec./ Freq.	Método de Control/ Control Method	Plan de Reacción / Reaction Plan
00	Receiving Inspection Shield	Received Component			Component Dimensions	◇	Component Dimensions		20 pc.	Each Lot	Component Print	-Segregate Suspect Material -Document Quality Issue -Contact Responsible Engineer -Return Out-Of-Spec Material to Supplier
	Receiving Inspection Terminal	Received Component			Component Dimensions	◇	Component Dimensions		20 pc.	Each Lot	Component Print	-Segregate Suspect Material -Document Quality Issue -Contact Responsible Engineer -Return Out-Of-Spec Material to Supplier
	Receiving Inspection Terminal Lock	Received Component			Component Dimensions	◇	Component Dimensions		20 pc.	Each Lot	Component Print	-Segregate Suspect Material -Document Quality Issue -Contact Responsible Engineer -Return Out-Of-Spec Material to Supplier
10	Cut Wire to Length	Wire Cutter			Wire Length		Wire Length	Check Print Dimension Tool Metric Graduated Ruler or Equivalent	1 pc.	100%	Measurement Aid	If wrong length, discard wires.
					Wire Insulation Integrity		No process induced deformations in insulation	Visual Inspection	1 pc.	100%	Measurement Aid	If nicked, cracked or split, discard wires.
20	Wire Strip and Terminate	Wire Stripper Crimp Press			Crimp Integrity		Pull Force Specification	Check Print Requirement Tool Wire Pull Tester	5 pc.	Tooling Change/ Start of Run	Wire Pull Tester Controller	If crimps display insufficient strength, verify set-up and tooling. If problem persists, contact engineering.
					Crimp Dimensions		Crimp Dimensions	Check Print Dimension Tool Calipers	5 pc.	Tooling Change/ Start of Run	Measurement Aid	If crimps display improper dimensions, verify set-up and tooling. If problem persists, contact engineering.
30	Assemble Connector	Manual			Wire Orientation		Wire in proper connector cavities	Visual Inspection	1 pc.	100%	Visual Aid	If wires oriented wrong (wrong cavity), disassemble and reassemble.

Rutina de Proceso: Plan de control de Proceso /
Process Routing: Process Control Plan

■ **Prototipo/ Prototype** ☐ **Pre-lanzamiento/ Pre-launch** ☐ **Producción/ Production** **Ultima Rev. de Plano/ Print Rev.:** **Número de Parte/ Part Number: F-EOSP-HARNESS-001**

#Cambio / Chg #	Fecha / Date (rev)	Ing. De Procesos/Herramientas / Process/Tool Engineer	Ingeniero de Calidad / Quality Engineer	Nombre de la Parte/Part Name: Exhaust Oxygen Sensor Harness	Pag./ Page:
		S. Bergman		Nombre del Producto/Product Name: Exhaust Oxygen Sensor	Dept.:
	Fecha / Date (orig)	Aprobación de Ing. Del cliente/Fecha / Cust. Engrg Apvl./ Date (If req'd)	Aprob.calidad del cliente/Fecha/ Cust. Quality. Apvl./Date(if req'd)		
	PCP#			Contacto Clave/Tel/Key Contact/Phone:	
				Planta/Código Prov. / Plant/Supplier Code:	

Equipo Principal / Core Team:

# Op	Descripción de la Operación / Operation Description	Máquina / Machine	Características / Characteristics: No.	Producto / Product	Proceso / Process	Caract. Especial / Special Charact.	Métodos / Methods: Espec. De Prodcuto/Proceso/ Product/Process Specification	Técnicas de Eval./ Medición / Eval./Measurement Technique	Tamaño de Muestra/ Sample Size	Frec./ Freq.	Método de Control/ Control Method	Plan de Reacción / Reaction Plan
50	Shield, Ceramic Terminal Lock and Seal Attach	Manual			Shield Orientation		Proper shield orientation	Visual Inspection	1 pc.	100%	Visual Aid	If shield oriented wrong, disassemble and reassemble.
					Ceramic Terminal Lock Orientation		Proper ceramic terminal lock orientation	Visual Inspection	1 pc.	100%	Visual Aid	If ceramic terminal lock oriented wrong, disassemble and reassemble.
					Seal Orientation		Proper seal orientation	Visual Inspection	1 pc.	100%	Visual Aid	If seal oriented wrong, disassemble and reassemble.
					Wire Orientation		Each wire in proper seal hole and proper ceramic terminal lock hole No crossed wires between seal and ceramic terminal lock	Visual Inspection	1 pc.	100%	Visual Aid	If wires oriented wrong (wrong hole or crossed), disassemble and reassemble.
60	Wire Strip and Terminate	Wire Stripper Crimp Press			Crimp Integrity		Pull Force Specification	Check Print Requirement Tool Wire Pull Tester	5 pc.	Tooling Change/ Start of Run	Set-up Instructions	If crimps display insufficient strength, verify set-up and tooling. If problem persists, contact engineering.
					Crimp Dimensions		Crimp Dimensions	Check Print Dimension Tool Calipers	5 pc.	Tooling Change/ Start of Run	Measurement Aid	If crimps display improper dimensions, verify set-up and tooling. If problem persists, contact engineering.
70	Terminal Weld	Welder			Weld Penetration		100% pooled weld zone	Check Weld Zone Tool Microscope	5 pc.	Tooling Change/ Start of Run	Set-up Instructions	If weld zone is out of specification, adjust weld parameters into specified range and recheck. If weld zone is still not to specification, contact responsible engineer.
80	Terminal Seat	Manual			Terminals Seated		Terminals fully engaged in ceramic terminal lock	Visual Inspection	1 pc.	100%	Visual Aid	If terminals are not fully engaged, attempt to lock. If terminals will not fully engage, hold for rework.
					Terminals Not Damaged		Proper terminal geometry	Visual Inspection	1 pc.	100%	Visual Aid	If terminals are damaged, hold for rework.

Delphi Energy and Chassis Systems – Bills of Process are **UNCONTROLLED DOCUMENTS FOR REFERENCE ONLY**

Process Development Action Plan

- **Investigate Commonization of Processes and Components with Wide Range**
  Rationale: Reduce costs through commonization

- **Investigate Overmolding Vehicle Connector**
- **Investigate Generic Vehicle Connector Terminals**
  Rationale: Reduce component cost
  Increase design flexibility

- **Investigate Elimination of Sensor Connection System Termination Welds**
  Rationale: Reduce costs through process step elimination

- **Investigate Elimination of Sensor Connection System Termination Welds**
  Rationale: Reduce costs through process step elimination

Appendix D

Bill of Design

Bill of Design

The Bill of Design Rationale

There is an immense collection of knowledge within organizations that is not exploited simply due to the fact that personnel do not know it exists. Consolidated best practices repositories are created to solve this problem. Best practices repositories allow an organization's knowledge to be centrally captured and universally communicated. This provides accessibility to the knowledge. It also enables decisions to be made based on the collective knowledge of the organization. In general, these repositories increase knowledge exploitation by providing accessible information for the entire organization.

The bill of design is a best practices repository framework. The bill of design is comprised of a list of specifications required for the design of a product utilizing proven design fundamentals. Bill of design incorporates design for manufacturing, design for assembly, design for serviceability and design for environment tools in order to create best practices to meet the expectations of the customers. Additionally, industry standards and internal best practices are incorporated in bill of design development to assure that customer specific requirements are not overlooked.

The bill of design is interconnected with the bill of materials and bill of process. Best practices developed for one framework must be inputted into the others in order to achieve overall best practices. Other information from inside and outside an organization should also be inputted to create the broadest data set available. This creates an iterative and interconnected development of best practices that once institutionalized in an organization can create a competitive advantage.

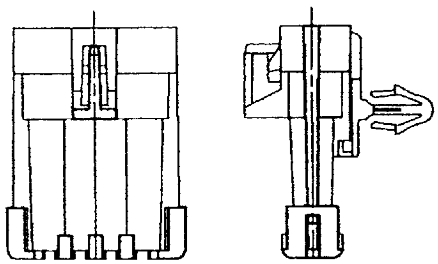
Exhaust Oxygen Sensor Specific Bill of Design Recommendations

The bill of design best practices framework appears to be most relevant when the entire product is considered. Since the interactions between the sensor and harness have a considerable effect on overall product functionality, creating a separate bill of design for the exhaust oxygen sensor harness may not produce beneficial best practices.

Information obtained from prototype system harness production and from benchmarking study lessons learned suggests potential best practices for the harness. After further investigation, these best practices can be incorporated in the exhaust oxygen sensor specific bill of design.

Lessons from the benchmarking study produced insights regarding technology trends in the industry. While some of these trends can not be immediately incorporated into the exhaust oxygen sensor harness, it is essential to understand the technological direction of the industry in order to build the competencies necessary to compete as these technologies become the customers' needs. Despite the limited differences in the benchmarking study population, lessons learned that could potentially become best practices were determined. There were lessons learned for each of the three harness sub-blocks, the vehicle connection system, the signal transfer system and the sensor connection system.

The Vehicle Connection System



The vehicle connection system is typically comprised of a plastic connector and electrical terminals. The purpose of the connection system is to connect the on-board computer and the electrical system in the vehicle to the sensor through the harness. This allows electrical signals to be interchanged.

In the Energy and Chassis Systems division baseline harness, the signal transfer system had two basic subsystems. While there were minor material and part count differences; the other harnesses in the benchmarking study had the same two basic subsystems.

1. The vehicle connector
2. The electrical terminals

There were numerous differences in both of the basic subsystems of the vehicle connector system. The vehicle connector tends to be the dictating design since the electrical terminals are used to connect the wires in the signal transfer system to the vehicle connection system.

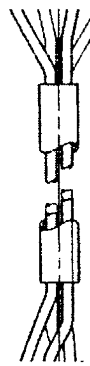
While most vehicle connectors were assembled using purchased components from electrical connector and interconnection systems suppliers, several were internally manufactured. Among the internally manufactured, the most promising design from a best practices perspective was the overmolded design. In the overmolded designs, the vehicle connectors were molded over the terminated wires. This is in contrast to the assembled vehicle connectors that have inserted terminated wires.

Overmolding the vehicle connector permits production of connectors that contain the exact features required. This eliminates the additional cost of the extraneous features that are often found on standard purchased connector components. Similarly, when new designs dictate additional connector features that are not readily available, overmolding allows components to be rapidly developed to meet the new customer needs.

There are effects of overmolding on other harness features. The vehicle connector terminals can be made generic since there are no insertion requirements. This can reduce material and processing costs of these terminals. Overmolding can also positively effect environmental protection of the signal transfer system. This can be accomplished by overmolding a small portion of the protective sleeve or insulation covering the wire set at the vehicle connector to enable complete coverage of the wires.

As a potential best practice, overmolding offers flexibility in vehicle connector design, which also positively effects other harness features. In the long-term, this flexibility may be critical in offering 'smart' sensors with embedded electronics in the vehicle connector. Developing competencies in overmolded vehicle connector processing will aid in fulfilling a potential future need of electronic customization through the addition of embedded printed circuit boards. These competencies may also foster speed-to-market through the ability to rapidly develop new vehicle connectors.

The Signal Transfer System



The signal transfer system is typically comprised of wires and electrical terminals. Additionally, it may have environmental protection devices to protect the wires during vehicle operation. The purpose of the system is to electrically connect the vehicle connection system to the sensor connection system to allow the harness to pass electrical signals. These electrical signals are passed between the on-board computer and the electrical system in the vehicle on one end and the sensor on the other end.

In the Energy and Chassis Systems division baseline harness, the signal transfer system had two basic subsystems. While there were minor material and part count differences; the other harnesses in the benchmarking study had the same two basic subsystems.

1. The terminated wires
2. The environmental protection device

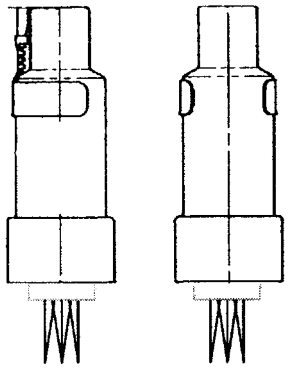
Differences in the wiring portion of the terminated wires were mainly cosmetic. As discussed in the vehicle connection system section of this appendix, the vehicle connector end terminations had diverse features. Similarly, as will be discussed in the sensor connection system section of this appendix, the sensor connector end terminations were completed with various processing technologies.

The exhaust oxygen sensor harnesses all had a protective sleeve for environmental protection of the signal transfer system's wires. This protective sleeve did not completely cover the wires from vehicle connector to sensor connector. In contrast, the non-exhaust oxygen sensor harness had an insulating shield completely covering the wires from vehicle connector to sensor connector.

As the analysis of failure mechanisms suggested, structural failures in the signal transfer system do occur. Vehicle connector to sensor connector coverage with an appropriate environmental protection material may be able to prevent structural failures in the signal transfer system.

As it was on the non-exhaust oxygen sensor harness, this complete environmental protection can be accomplished by using an insulator-covered wire set. Investigation of the tradeoffs between the additional material and processing costs of the insulator-covered wire set and the elimination of material and processing costs of the protective sleeve should be conducted to determine if this is a best practice to maintain signal transfer system robustness.

The Sensor Connection System



The sensor connection system is typically comprised of insulating ceramic components, structural metallic components, sealing components and electrical terminals. The purpose of the connection system is to connect the sensor to the on-board computer and the electrical system in the vehicle through the harness. This allows electrical signals to be interchanged.

In the Energy and Chassis Systems division baseline harness, the sensor connection system had four basic subsystems. While there were minor material and part count differences; the other exhaust oxygen sensor harnesses in the benchmarking study had the same four basic subsystems.

1. The insulating ceramic components
2. The metallic structural components
3. The sealing components
4. The electrical terminals

Differences in the insulating ceramic components and the metallic structural components were minor. These differences did not appear to suggest that any one design had a competitive advantage. The sensors that attached to these components appeared to dictate the differences.

The sealing mechanism in the majority of the harnesses was an elastomer. However, one harness incorporated the sealing components and insulating ceramic components in an apparent attempt to reduce component stack-up. Reduction in stack-up did not appear to be a substantial justification for the additional cost of manufacturing the intricate component. Additionally, changing the other harness components to compensate for the integration would increase costs with little benefit.

While size and shape differences in the electrical terminals were most likely due to disparities in the mating sensors, the electrical terminals across the harness were processed using diverse methods. The terminals in all harnesses were crimped to the signal transfer system wires. Beyond the crimp, however, processing was varied. While most harness terminations were welded, several had only the crimp. Among the terminations with welds, some were laser welded, some were plasma welded and some were resistance welded.

The harnesses without the welds might have exceptional terminal crimp quality that renders the weld redundant. The division's internal data suggests that the weld is necessary to assure zero defects in the field at these terminations. Elimination of the weld process step would be a cost-effective best practice if further investigation suggests crimp quality can be controlled well enough to make the weld redundant.

The differences in termination weld processing are most likely due to available technology and expertise within the respective harness manufacturers. From a lean and cost perspective, resistance welding is the best process choice provided that the materials in the product are designed to allow for it. Where possible, products should be designed to allow for resistance welding of the terminations.

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