INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'07
28 - 31 AUGUST 2007, CITE DES SCIENCES ET DE L'INDUSTRIE, PARIS, FRANCE

A RESEARCH ROADMAP FOR PRODUCT FAMILY DESIGN

John K. Gershenson, Kiran N. Khadke, and Xiaoxia Lai
Life-Cycle Engineering Laboratory, Dept. of Mechanical Engineering-Engineering Mechanics, Michigan Technological University

ABSTRACT
Product family design is a complex and multi-faceted research topic. It is necessary to approach this topic in a piece-wise fashion and that is what the design research community has been doing with significant help from the marketing and product development research communities. However, to approach this very large topic without a roadmap that defines the necessary pieces, their relationships, and the manner in which they build upon each other will obviously delay the achievement of the goal and cause great inefficiencies. For that reason, we propose in this paper an initial research roadmap to lead the discussion among the research community in coalescing their individual efforts to achieve a collective research goal. The single goal that this research roadmap shows is the achievement of product family design methods. The roadmap is broken down into three layers – single product factors, product family factors, and over-time factors – each requiring significant research on multiple topics. It is our hope that, using this roadmap, researchers will continue this discussion to maintain a dynamic roadmap that allows each of us to have a clearer concept of the role of our individual research in the larger community's goals. Additionally, those that are typically outside of the design research community will better understand their role in achieving this collective goal. This research roadmap is not intended to diminish the need for nor the goals of individual research projects. Many of these smaller topics within the research roadmap are important, implementable design research goals in themselves. However, if the outcomes are stated with this roadmap or a future one in mind, these individual projects may also serve a greater goal.

Keywords: product family design, product platform design, modular product design, research roadmap

1 INTRODUCTION
This paper develops a research 'roadmap' for product family design and decision-making methods. A significant amount of research has been reported in the areas of product modularity, product platforms, and product families over the last 25 or so years. The aim of our paper is to build upon this knowledge with an eye towards the future. As such, we define the key elements, methods, tools, and information necessary to achieve the vision of product families as well as how each of these pieces is linked together. Before introducing the roadmap, it is first necessary to define the terms of modularity, platforming, and product families that we will use and to take a brief look at the existing research.

1.1 Concepts and terminology
This research roadmap is based upon work in marketing, technology management, product development, and engineering design in the areas of product modularity, product platforms, global product platforms, and product families. These terms have been used in many different ways and, along with what we mean by a research roadmap, are summarized below, followed by our interpretation of each term.
Research Roadmap: Roadmaps are defined as the views of a group of stakeholders as to how to get where they want to go to achieve their desired objective [1]. It is an extended look at the future of a chosen field of inquiry [2].

For the purposes of this paper, a research roadmap, different from a traditional roadmap, is projected as a technique for exploring and communicating the linkages among foreseen research projects and to a larger research goal in a research field. Our larger research goal is design and decision-making methods for realizing robust product family design.

Modularity: Ulrich and Tung [3] defined modularity in terms of two characteristics of product design: "1) similarity between the physical and functional architecture of the design and 2) minimization of incidental interactions between physical components." Ulrich and Eppinger [4] define modularity in terms of product architecture and product function - a modular architecture includes "chunks" implementing "one or a few" functions, with few if any interactions. Dahmus *et al.* [5] define product modules architecturally as sub-systems within a product that are bundled as a unit, and which serve identifiable functions. A similar definition applying to assemblies states that, modularity refers to physical or conceptual groupings of the various components within an assembly [6]. An expanded definition of product modularity for life-cycle processes is given in Gershenson *et al.* [7] - modules contain a high number of components that have minimal dependencies upon and similarities to other components not in the module during their life-cycle. Additionally, a module is defined as a component or group of components that can be removed from the product non-destructively as a unit, which provides a unique basic function necessary for the product to operate as desired [8]. Lastly, a more general and encompassing definition is that, modular products refers to the products, assemblies, and components that fulfill various functions through the combination of distinct building blocks (modules) [9]. A more in depth study of the definition of product modularity can be found in Gershenson *et al.* [10]. For the purposes of this research roadmap, we are using the term modules to mean chunks of products characterized by high similarity within and few dependencies with components outside of them - controlled by design.

Platforms: A platform is a very special instantiation of a module (or cluster of modules) that can drive the design of product families. A platform is a set of "common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched" [11]. In a slightly broader definition of the physical platform, it is a "collection of the common elements, especially the underlying core technology, implemented across a range of products" [12]. However, as with product modularity, there is an opportunity to look past just the physical element of a platform to look at is as a "collection of assets (*i.e.*, components, processes, knowledge, people and relationships) that are shared by a set of products" [13]. To this list of assets we would also add functions, attributes, and technologies. For the purposes of this research roadmap, we are using the term platforms to mean architectures that support more than one product characterized by common structures, scaled structures, and variable structures - controlled by design. This is applied to the physical architecture of the product, but it is based upon the collection of assets that Robertson and Ulrich [13] discuss.

Product family: A product family is the collection of products that share the same assets (*e.g.*, a platform) [14, 15]. Additionally, the family is a set of products that share common technology and address a related set of market application [11]. A more general description of the use of the product family is a group of related products that is derived from a product platform to satisfy a variety of market niches [16].

For the purposes of this research roadmap, we are using the term product family to mean groups of products characterized by common physical structures, functions, and/or markets - controlled by the market, marketing, and design.

Global platforms: Global platforms differ from traditional platforms as they are specified alone, without the presence of a product family. Global platforms are the core of a globally rolled-out product. A global rollout plan details the aspects of the product that can be / should be standardized as well as those aspects that should be adapted to country-specific conditions and to customer preferences. Customization can involve physical changes in the product and adaptation in pricing, service, positioning message, or channel [17]. For the purposes of this research roadmap, we are using the term global platform to mean a set of common structures developed as building blocks to be used for the creation of many different, and as yet not designed, products by a variety of different design organizations possibly leading to a product family.

1.2 A brief product family development background

Product family design begins with exhaustive market studies. The key question to be answered is - which product variants will be preferred by customers? With diverse customer requirements and preferences it becomes necessary to group these needs and identify their relevant importance for reasons of design and manufacturing. To aid in this task, often referred to as market segmentation, Green and Krieger [18] introduce a conjoint analysis method to measure and group customer preferences. Meyer and Lehnerd [11] introduce another method, the market segmentation grid method to identify the different levels in the market. Ulrich *et al.* [19] also discuss how to generate the market segmentation for multi-product firms.

Not all existing market segments create the same opportunity for different companies in the same industry due to the discrepancy of their targets, strategies, technologies, cultures, *etc*. [16], thus highlighting the challenge of platform and product family positioning. While platform positioning focuses on the design of the optimal number of platforms and how to map the platforms to market segments [11], the central problem in product family positioning is how to offer the right product variety to the right target market [16, 20, 21].

The objective of platform-based product family design is to lower cost, which can be achieved by improving the commonality between the products within the product family. A number of commonality indices have been developed to guide the designers in improving commonality [22-28]. However, it should be noted that too much commonality or inappropriate commonality among the products would lead to a loss in performance distinctiveness, and consequently decrease the diversity of customer choice. Du *et al.* [29] classify two types of variety: functional variety and technical variety. These two types of variety motivate two different design strategies [16]. Design for functional variety aims at satisfying diverse customer requirements [30-32] while design for technical variety reduces the "in-house" variety through postponement [33], function sharing [34], modular design [35], and reconfiguration [36]. Unlike the commonality indices, a variety index that is suitable in the design of product families is yet to be developed [37].

There are two basic approaches to product family design [38]: top-down and bottom-up. Top-down approach begins with either customer needs or functions or design engineering metrics [39, 40], while a bottom-up approach begins with detailed information such as design variables, components, production processes, component cost information, *etc.* [41]. Whichever approach is chosen, it is still necessary to identify and organize the elements into platforms and variants. A number of methods are reported in the literature to help make these decisions including optimization techniques [41-44], fuzzy clustering and ranking methodologies [45], and configuration reasoning systems [46].

The identified platforms are also supposed to be scalable [47] and configurable [48], and should take into account the products' life-cycle processes and a company's resources and strategies. A set of evaluation metrics to evaluate platform alternatives and drive the selection of platforms is provided by Holtta and Otto [49]. To assess and solve the tradeoff problems during the product family design, methods such as PFEG [37] and the profitability maximizing method [50] have been developed. By combining the appropriate platforms and scalable or optional variants, the right product family can be provided to customers.

Modular architecture is considered very important for product family design [16]. Not only does it facilitate the manufacturing, upgrading, outsourcing of products as it does in single product design, but modularity also impacts the trade-off between commonality and variety [13]. The configurational approach to product family design is based on the successful development of modular product architecture [51]. Jiao *et al.* [16] state that three types of product modularity - functional modularity, technical modularity, and structural modularity - lead to three types of corresponding commonalities in product family design. However, the differences between modular design for a single product and for a product family, and the development of a systematic modular product family design method are issues that are yet to be fully addressed.

Another growing area of research within product family design concerns the development of process platforms. Williams *et al.* [52] discuss a design methodology for realizing process parameter platforms that could help to generate a customized product efficiently despite changes in capacity requirements. In addition, configuration models that can incorporate manufacturing and supply chain issues for product families have been developed with the aim of introducing customization late in the product realization process [53-56].

The goal of this paper is to tie these disconnected pieces of research together, along with yet to be done research, into a roadmap for developing a method of robust product family design. We hope that this roadmap can be a guide to both future research/project decision-making as well as a guide to link these projects based upon inputs and outputs.

2 RESEARCH ROADMAP OVERVIEW

It is our aim to present a roadmap to achieve fundamental design decision making to support the design of product families (and global product families) that incorporate product platforms and the life-cycle benefits of product modularity. The work presented here has evolved from and is a result of our close association and communication with other researchers, and active participation in the research community. Thus, this roadmap is not just what our research group will do over the next few years. We present here an initial community roadmap that also relies on those outside our research community to build the necessary capabilities and design elements in supporting layers. When we refer to the community we include the academic and industry researchers and practitioners who are working to achieve robust product families and design methods to realize them systematically.

It is imperative that this roadmap be accomplished in a layered and measured manner to allow for reflection and feedback on both the elements of the roadmap and their connections. Each of the blocks in the roadmap is a step towards a single end product, a design process for robust product families. As such, following this roadmap will take some discipline to avoid going for the end product prematurely or to avoid developing elements for purposes other than the one on this roadmap.

Our layered approach entails achieving systematic design capabilities (design methods) that build upon one another to achieve the final goal of robust product family design. Based upon the application of these methods, combinations of these pieces can be useful in their own right. The three elements of the roadmap are Single Product Modular Product Design, In-Time Product Family Design, and Over-Time Product Family Design. Modular product design (MPD) and product family design (PFD) were defined previously. MPD will serve as a fundamental piece of PFD. Therefore, to realize PFD methods, we need to develop both MPD methods and PFD methods. MPD is the application of the concepts of this roadmap to a single product; whereas PFD is the application to multiple products (*i.e.*, a product family). This represents the first delineation within the research roadmap; the delineation between those elements that impact single product design and those that impact product family design. In achieving the end goal of this research roadmap, we would begin with the fundamental step of developing a systematic method for realizing MPD within single products and add to this the elements that enable designing for multiple products to realize PFD.

The next delineation in this roadmap is between the design factors that are static or representative of a particular product/product family snapshot, what we call in-time factors, and those factors that incorporate a dynamic nature that typically change over time, what we call over-time factors. Together, MPD and PFD must capture all of the in-time factors at a minimum. It is best to begin with these in-time factors and validate the methods with respect to static applications. Once validated, we can add to these methods with over-time factors - technological change, market change, and life-cycle process change. Technological change includes factors that affect the principle of operation, the performance and the architecture within a product. Factors that relate to market change include changes in customer demand, competition, and customer buying power [37]. Life-cycle process change factors encompass the processing and post-processing of a product such as assembly and retirement [57]. Keep in mind that “correct” PFD should incorporate all of the elements in Figure 1, but we are defining the research roadmap at this point, not the methodology. The research roadmap is a build up of layers.

With in-time and over-time factors accounted for and the related PFD methods validated, there would exist the systematic PFD capabilities to incorporate both static and dynamic elements and make use of MPD to design intelligent platforms and product modules that capitalize on opportunities for commonality and variety due to technology, the market, and life-cycle processing.

3 RESEARCH ROADMAP SPECIFICS

The previous section presented the research roadmap in broad strokes and defined the layered approach that we are advocating. In this section, we will detail the work that is necessary to achieve the roadmap. Some of this work is already complete. However, our goal is to show the linkages among the research topics and how they support a final goal - robust product family design. The entire roadmap is shown in Figure 1. The roadmap is split into the three areas that were discussed previously – single products, product families, and over-time factors. Together, single products and product families encompass the in-time factors.

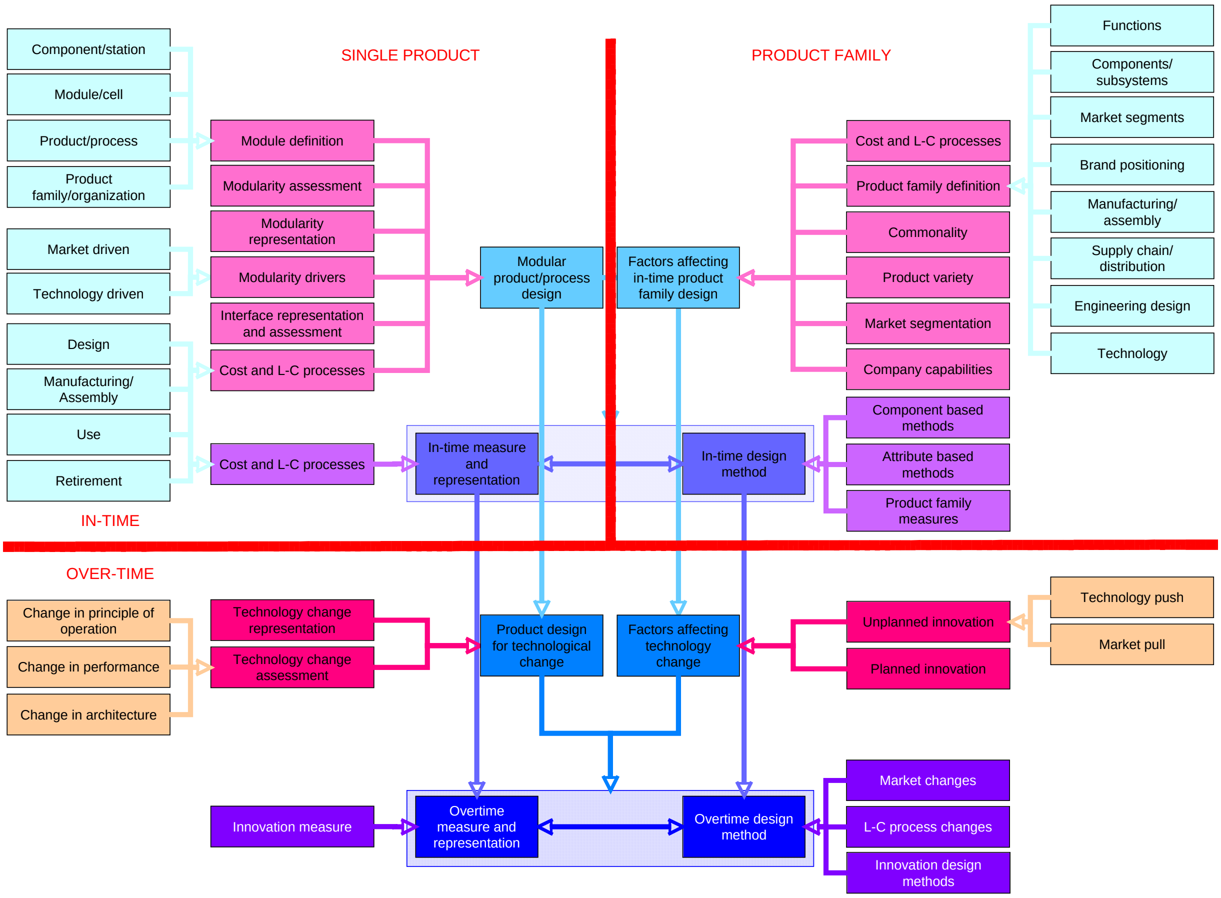

Figure 1: Product family design research roadmap

3.1 Single product factors

The key question that we must answer here is, how to systematically achieve modular product design? The goal is to develop design methods to modularize a product to satisfy design, manufacturing/assembly, use and retirement intent. The available input is the existing product definition in the form of function and/or component relationships. The expected output must be modules with minimum dependencies between them and as much similarity as possible within them. To answer the key question, we look at five more specific questions: how to define, represent, and assess modules; at what level should the modules be defined; how to define, represent, and assess the interfaces between the modules; what is the effect of taking a life-cycle perspective on modular design; and how does the drive (market or technology) for modularity affect the modular design process. The relationship among the single product factors research topics is shown in Figure 2.

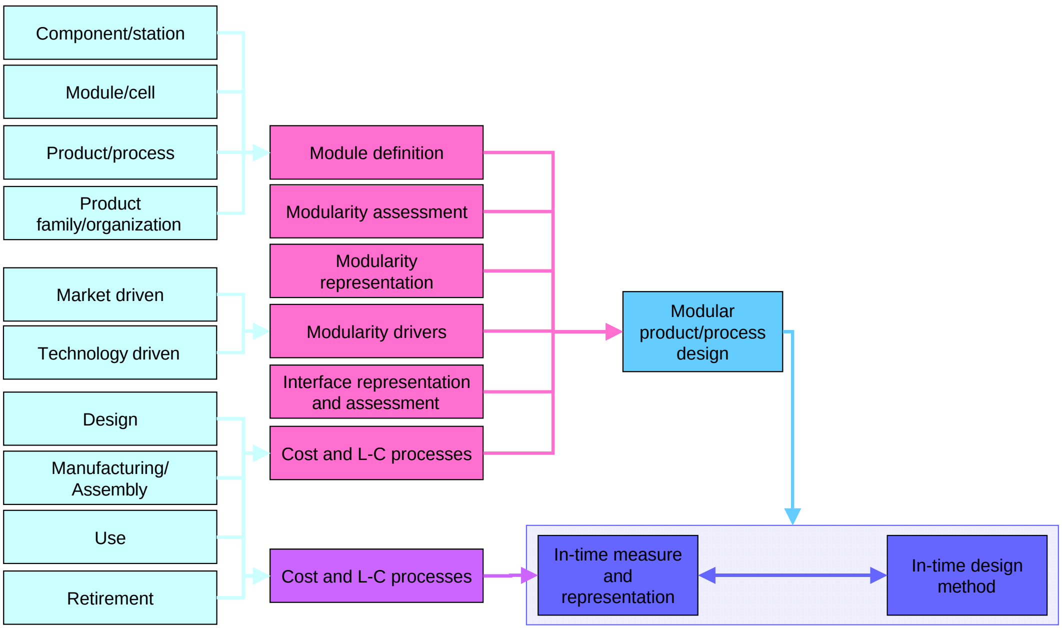

Figure 2: Single product factors research roadmap close-up

The development of modular design methods has been an ongoing research topic with results seen in the work by Coulter *et al.* [6], Gershenson *et al.* [7], Guo *et al.* [58, 59], Huang and Kusiak [55], Lai *et al.* [57], and Stone *et al.* [60]. Work is yet to be completed that comes to some conclusion on a modular design method that is robust, efficient for complex systems, and validated in a product development environment. As part of this development, we must consider the issues of assessing the degree of modularity and how to represent modular product architectures in the design process. Consensus has been reached on the use of similarity and dependency as both the fundamental building block of modular product design as well as the basis for modular assessment. Similarly, matrix-based representations similar to the design structure matrix [61] and based upon some product or process breakdown similar to the function-structure method are widely accepted. The next step is, again, to validate these methods on complex products and within a real product development environment.

The question of a necessary or "optimal" level of modularity is one that can not be addressed without a robust modular design method and a comprehensive measure for assessing product modularity. It may be necessary to refine general modular design methods to make them more applicable at specifically the component, module, product, and product family (as we move on in this roadmap) level. The open research question is, how are these "modular" aggregations different and what is the impact of each on modular design methods?

How to define, represent, and assess the interfaces between or among modules is a question that was studied in great depth in the beginning of modular research, but that work has since waned. Pahl and Beitz [62] looked at an interface design method in broad terms and many have discussed the importance of interface commonality in modular design, but no work has surfaced that has led to interface design methods. Chen and Liu [63] examined the role of compatibility and complimentarity [*sic*] in interface assessment and Bettig and Gershenson [64] discussed the role of interface representation in a CAD/PDM environment. However, a design method to specify the different types of interfaces among modules and the interface attributes is still needed.

The remaining work with potentially the largest impact on the role of modular design in product development is centered around the question, what is the effect of taking a life-cycle perspective on modular product design. Most modular design is function-oriented; some is market driven or technology driven; occasionally we see work that has at its goal the modularization of products to facilitate a particular life-cycle process (typically assembly or product retirement). However, what would the module definition look like if the entire life-cycle was accounted for in the design process? The result, assuming that modular design is cost beneficial when applied correctly, would be a decrease in total life-cycle cost.

While researchers have begun to address this topic, the rush to achieve product family design for functional and market-based goals has led to placing this topic on the back burner. The application and assessment of modularity and the definition of similarity and dependency is necessarily complex as it is applied across the life-cycle.

One additional research question that will change the single product modular design process, and therefore impact product family design, is how does the motivation (market-driven or technology-driven) for modularity affect the modular design process. There are potentially other drivers as well, but in the end, we expect that all can be classified as either organizationally internal (technology development, life-cycle cost, *etc*.) or organizationally external (market pressure, customer need, *etc*.). These issues will be raised again, as will many issues, when researchers investigate over-time factors.

3.2 Product family factors

Obviously, much of this roadmap relies on the question, how to systematically achieve product family design? The goal is to develop a product family design method that considers the wide range of in-time factors. The available inputs are either a set of 'orphaned' products or customer requirements with their market segment information, as well as a method to affect product modularity. The expected output must be the classification of platform (common) elements/modules and variant (differentiating) elements/modules that constitute the products of the product family and still align with the desired market segments. The specific research questions that make up this larger question are similar to those that we see in modular design: how to define and assess product families; how to define and assess platforms within these families and when platforms should be used; at what level should product families be defined and in what situations are each of these and product families themselves beneficial; and what is the effect of taking a life-cycle perspective on product family design and process design. The relationship among product family factors research topics is shown in Figure 3.

Work has already begun on how to define and assess product families as we discussed in the background. Work is progressing in the use of measures of commonality and variety to assess the quality of the product family. There have been and need to be two approaches to product family, a top-down approach, where a family is created from a set of needs, and a bottom-up approach, where a family is created from a set of products.

What is missing in much of the current research is the role of these methods in the larger scope of this research and a connection to all of the in-time single product factors including modularity and life-cycle processes. Platforms, and their role in product families, have emerged as a central issue in product family design. Specifically, how to define and assess platforms within these families and when platforms should be used are significant research questions that must be addressed. Having a validated foundation in modularity assessment and modular product design will be necessary, as platforms rely heavily on the science of product modularity. However, the issues of commonality, scale, and uniqueness across families and within families need also be incorporated. In addition, the knowledge gained from defining module interfaces will be very similar to platform interfaces.

As with single product modularity, defining at what level product families should be based is important to their application within product design. Families can be built based upon commonality and variety in functions, components and subsystems, market segments, brand positioning, manufacturing, supply and distributions chains, design processes, or technology. Researchers must first understand how to accomplish each of these individually and the differences in product family design methods among them, then we can look to combine these levels of product family design and define at which level design should take place based upon the presence of various in-time (and later over-time) factors. To accomplish this it is also necessary to clearly understand the impact of the product family design decisions on life-cycle cost. Depending upon the level and the scope, it may be necessary to use differing design methods and measures or a combination of them. Some focus more on the physical/component level of the product, while other methods focus more on their engineering attributes. The latter is especially useful early in the design process.

Understanding the impact on life-cycle cost brings us to the last product family factor, the role of the life-cycle processes in product family design. What is the effect of taking a life-cycle perspective on product family design and how can process design, or perhaps process family design, be incorporated into product family design? Research must be done to define what is a product family that is designed for commonality or variety in design processing, manufacturing, assembly, use, service, retirement, *etc.* and when is it beneficial in terms of life-cycle cost to expand the scope of product family design to include these factors.

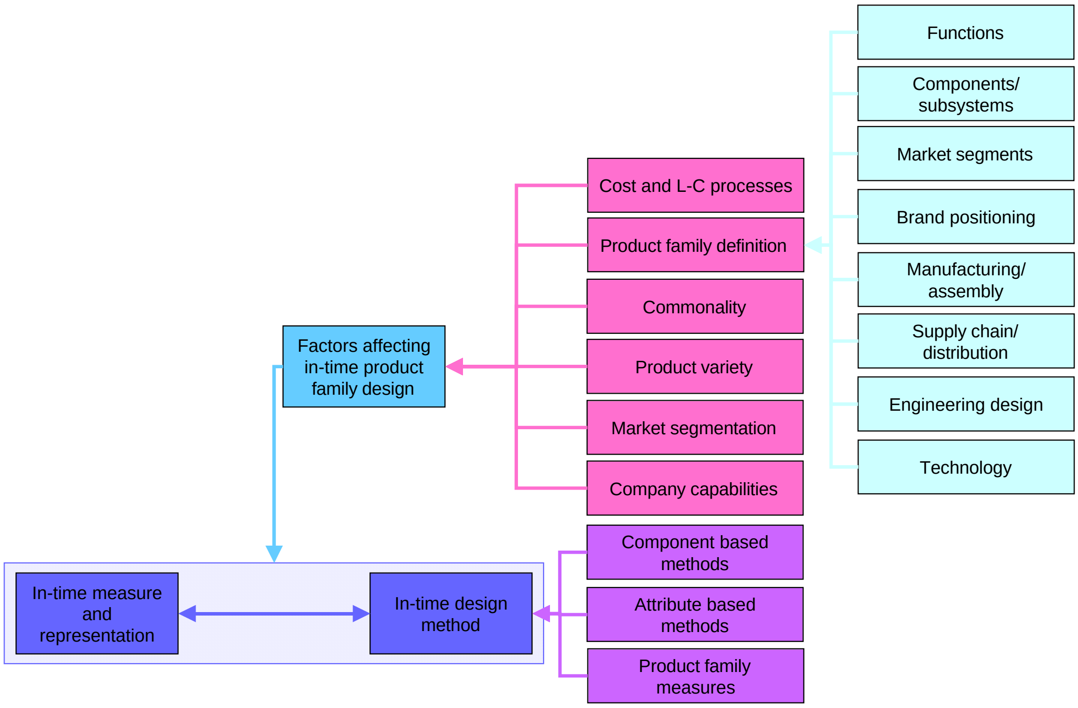

Figure 3: Product family factors research roadmap close-up

3.3 Over-time factors

Together, single product modularity and product family design research should tackle all of the static factors influencing product family design. Once these are understood and validated, the next logical question is, how does the inclusion of dynamic factors that change over time affect product family design? The goal is to develop product family design methods that account for not only the current state of factors, but also their planned changes over the life of the family. The available inputs are in-time product family design methods, dynamic factors (market change, technological change, and life-cycle process change) and their relationships with product design. The expected output must be members of a product family that are both planned with respect to these identified dynamic factors and can be easily upgraded in face of the factors. Some of these over-time factors result in a need for what we call technological change. Specifically, we must know what factors affect technological change and how to define, assess, and represent technological change. The relationship among over-time factors research topics is shown in Figure 4.

Obviously, the first question is, what factors affect technological change? Marketing and product development research has been looking at this question for some time. However, the results have not been satisfying from an engineering design perspective. Clearly, there is a need for both planned and unplanned innovation in product development. Unplanned innovation is often due to either the external push of technology or the external pull of the market place. Planned innovation is often due to the more careful march of research and development and perceived market opportunities. It is necessary to define technological change and its relationship to the elements of product design that engineering design can control – principle of operation, performance, and product/process architecture. Incorporating all of the previous elements of this roadmap as potential factors affecting technological change and seeing how they do change over time will enable a dynamic, over-time view of product family design that is again more complete. Perhaps the most significant advantage is the ability to plan and design for generational change within product families. In the end, we must be able to define, assess, and represent the widest variety of technological change. As one might expect from the overall research roadmap, this piece of the roadmap will require an even more cross-functional viewpoint.

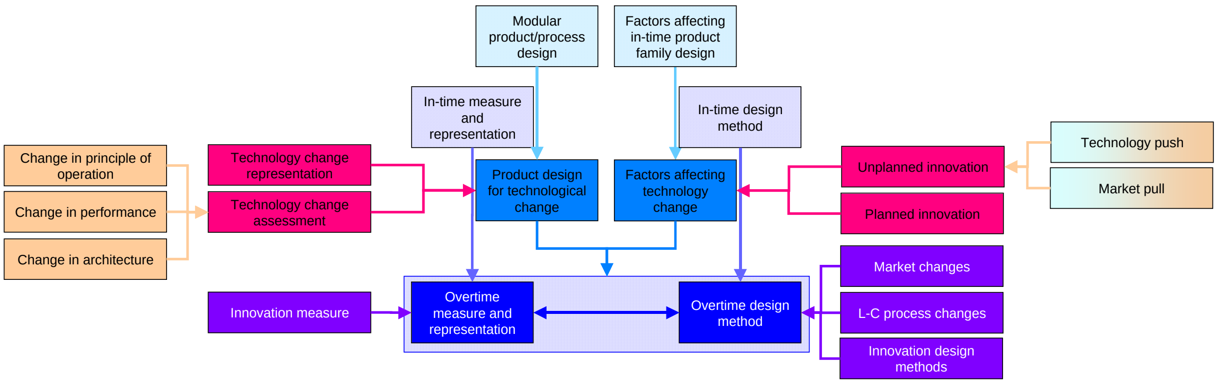

Figure 4: Over-time product family factors research roadmap close-up

4 CONCLUSIONS

In this paper, we have laid out an initial product family design research roadmap for the engineering design community and other supporting research communities. The ultimate goal of this research roadmap is to lead to methods of product family design that utilize product modularity and product platforming, taking into account commonality and variety across the life-cycle for static and dynamic factors. We have outlined a multitude of research questions built up in layers consisting of single product modularity factors, product family design factors, and over-time factors. Some of the significant distinctions in this map include: the role of single product modularity and platforming in product family design; the role of life-cycle processes as a basis for product family design; the separation of in-time and over-time product family design; the need for both a component-based and attribute-based approach to solve the larger issues of product family design; and the formalization of technological change as a driver for over-time product family design. There is much work to be done and, as with all roadmaps, the product family design roadmap is a dynamic, community-managed vision.

ACKNOWLEDGMENTS

We gratefully acknowledge the National Science Foundation, grant DMI-0323497, for enabling this work. Any opinions, findings and conclusions or recommendations presented in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

1. Lee, S. and Y. Park, Customization of Technology Roadmaps According to Roadmapping Purposes: Overall Process and Detailed Modules. Technological Forecasting & Social Change, 2005. 72: p. 567–583.
2. Kappel, T.A., Perspectives on Roadmaps: How Organizations Talk about the Future. Journal of Product Innovation Management, 2001. 18 (1): p. 39–50.
3. Ulrich, K. and K. Tung, Fundamentals of Product Modularity. Issues in Design/Manufacture Integration, 1991. 39: p. 73-77.
4. Ulrich, K., The Role of Product Architecture in the Manufacturing Firm. Research Policy, 1995. 24(3): p. 419-440.
5. Dahmus, J.B., J.P. Gonzalez-Zugasti, and K.N. Otto, Modular Product Architecture. Design Studies, 2001. 22(5): p. 409-424.
6. Coulter, S.L., *et al.* Identification of Limiting Factors for Improving Design Modularity. in Proceedings of the 1998 ASME Design Engineering Technical Conferences - 10th International Conference on Design Theory and Methodology. 1998. Atlanta, Georgia.

7. Gershenson, J.K. and G.J. Prasad, Modularity in Product Design for Manufacturing. International Journal of Agile Manufacturing, 1997. 1(1): p. 99-109.
8. Allen, K.R. and S. Carlson-Skalak. Defining Product Architecture During Conceptual Design. in Proceedings of the 1998 ASME Design Engineering Technical Conference - 10th International Conference on Design Theory and Methodology. 1998. Atlanta, Georgia.
9. Kusiak, A. and C.C. Huang, Design of Modular Digital Circuits for Testability. IEEE Transactions on Components, Packaging, and Manufacturing Technology, 1997. 20(1): p. 48-57.
10. Gershenson, J.K., G.J. Prasad, and Y. Zhang, Product Modularity: Definitions and Benefits. Journal of Engineering Design, 2003. 14(3): p. 295.
11. Meyer, M.H. and A.P. Lehnerd, The Power of Product Platforms: Building Value and Cost Leadership. 1997, New York, NY: The Free Press.
12. McGrath, M.E., Product Strategy for High-Technology Companies. 1995, New York: Irwin Professional Publishing.
13. Robertson, D. and K. Ulrich, Platform Product Development. Sloan Management Review, 1998. 39(4): p. 19-31.
14. Meyer, M. and J. Utterback, The Product Family and The Dynamics of Core Capability. Sloan Management Review, 1993. 34(3): p. 29-47.
15. Sawhney, M.S., Leveraged High-Variety Strategies: From Portfolio Thinking to Platform Thinking. Journal of the Academy of Marketing Science, 1998. 26(1): p. 54-61.
16. Jiao, J., T.W. Simpson, and Z. Siddique, Product Family Design and Platform-Based Product Development: A Start-of-the-Art Review. Journal of Intelligent Manufacturing, 2006. In print.
17. Halman, J.I.M., A.P. Hofer, and W. Vuuren, Platform Driven Development of Product Families: Linking theory with practice. Journal of Product Innovation Management, 2003. 20 (2): p. 149-162.
18. Green, P.E. and A.M. Krieger, Models and Heuristics for Product Line Selection. Marketing Science, 1985. 4(1): p. 1-19.
19. Ulrich, D. and M. Draganska, Market Segmentation Strategies of Multiproduct Firms. The Journal of Industrial Economics, 2006. 1(1).
20. Jiao, J. and Y. Zhang, Product Portfolio Planning with Customer-engineering Interaction. IIE Transactions, 2005. 37(9): p. 801-814.
21. Markus, A. and J. Vancza, Product Line Development with Customer Interaction. CIRP Annals, 1998. 47(1): p. 361-364.
22. Collier, D.A., The Measurement and Operating Benefits of Component Part Commonality. Decision Sciences, 1981. 12(1): p. 85-96.
23. Wacker, J.G. and M. Trelevan, Component Part Standardization: An Analysis of Commonality Sources and Indices. Journal of Operations Management, 1986. 6(2): p. 219-244.
24. Kota, S., K. Sethuraman, and R. Miller, A Metric for Evaluating Design Commonality in Product Families. Journal of Mechanical Design, 2000. 122(4): p. 403-410.
25. Siddique, Z., R. D. W., and W. N. On the Applicability of Product Variety Design Concepts to Automotive Platform Commonality. in ASME Design Engineering Technical Conferences - Design Theory and Methodology. 1998. Atlanta, GA.
26. Martin, M. and K. Ishii. Design for Variety: A Methodology for Understanding the Costs of Product Proliferation. in 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference - Design Theory and Methodology. 1996. Irvine, CA: ASME.
27. Jiao, J. and M.M. Tseng, Understanding Product Family for Mass Customization by Developing Commonality Indices. Journal of Engineering Design, 2000. 11(3): p. 225-243.
28. Thevenot, H.J. and T.W. Simpson. A Comprehensive Metric for Evaluating Commonality in a Product Family. in ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. 2006. Philadelphia, PA: ASME.
29. Du, X., J. Jiao, and M.M. Tseng, Architecture of Product Family: Fundamentals and Methodology. Concurrent Engineering: Research and Application, 2001. 9(4): p. 309-325.
30. Sanderson, S. and M. Uzumeri, Managing Product Families: the Case of the Sony Walkman. Research Policy, 1995. 24(5): p. 761-782.

31. Choi, S.C., W.S. Desarbo, and P.T. Harker, Product Positioning Under Price Competition. Management Science, 1990. 36(2): p. 175-199.
32. Kaul, A. and V.R. Rao, Research for Product Positioning and Design Decisions: An Integrative Review. International Journal of Research in Marketing, 1995. 12(4): p. 293-320.
33. Feitzinger, E. and H.L. Lee, Mass Customization at Hewlett-Packard: the Power of Postponement. Harvard Business Review, 1997. 75(1): p. 116-121.
34. Ulrich, K. and S. Eppinger, Product Design and Development. 1995, New York, NY: McGraw-Hill Higher Education.
35. Erixon, G. and B. Östgren. Evaluation Tool for Modular Design. in Forum on DFMA. 1993. Newport, USA.
36. Brabazon, P.G. and B. MacCarthy, Virtual-Build-To-Order as A Mass Customization Order Fulfillment Model. Concurrent Engineering: Research and Application, 2004. 12(2): p. 155-165.
37. Ye, X., *et al.* An Introduction to Product Family Evaluation Graphs. in ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference-11st Design for Manufacturing Conference. 2005. Long Beach, California: ASME
38. Simpson, T.W., J.R.A. Maier, and F. Mistree, Product Platform Design, Method and Application. Research in Engineering Design, 2001. 13(1): p. 2-22.
39. Zamirowski, E.J. and K.N. Otto. Identifying Product Portfolio Architecture Modularity Using Function and Variety Heuristics. in Proceedings of the 1999 ASME Design Engineering Technical Conference - 11th International Conference on Design Theory and Methodology. 1999. Las Vegas, Nevada.
40. Krishnapillai, R. and A. Zeid, Mapping Product Design Specification for Mass Customization, in *Journal of Intelligent Manufacturing*, A. Kusiak, Editor. 2006, Springer: New York.
41. Simpson, T.W., Z. Siddique, and J. JIAO, Proudct Platform and Product Family Design - Methods and Application 2005: Springer Science +Business Media, Inc.
42. Fellini, R., M. Kokkolaras, and P.Y. Papalambros, Commonality Decisions in Product Family Design, in *Product Platform and Product Family Design Methods and Application*, T.W. Simpson, Z. Siddique, and J.J. (Eds.), Editors. 2005, Springer: New York.
43. DeWeck, O.L., Determining Product Platform Extent, in *Product Platform and Product Family Design Methods and Application*, T.W. Simpson, Z. Siddique, and J. Jiao, Editors. 2005, Springer: New York.
44. Fujita, K., Product Variety Optimization, in *Product Platform and Product Family Design Methods and Application*, T.W. Simpson, Z. Siddique, and J. Jiao, Editors. 2005, Springer: New York.
45. Zha, X.F., R.D. Sriam, and W.F. Lu, Evaluation and Selection in Product Design for Mass Customization: a Knowledge Decision Support Approach. AIEDAM, 2004. 18(1): p. 87-109.
46. Siddique, Z. and D.W. Rosen, On Discrete Design Spaces for the Configuration Design of Product Families. Artificial Intelligence in Engineering, Design, Automation, and Manufacturing, 2001. 15: p. 1-18.
47. Simpson, T.W., J. Maier, and F. Mistree. A Product Platform Concept Exploration Method for Product Family Design. in Proceedings of the 1999 ASME Design Engineering Technical Conference - 11th International Conference on Design Theory and Methodology. 1999. , Las Vegas, Nevada.
48. Siddique, Z. and D. Rosen. Product Family Configuration Reasoning Using Discrete Design Spaces. in Proceedings of the 2000 ASME Design Engineering Technical Conference - 12th International Conference on Design Theory and Methodology. 2000. Baltimore, Maryland.
49. Holtta-Otto, K. and K. Otto, Platform Concept Evaluation, in *Platform and Product Family Design Methods and Application*, T.W. Simpson, Z. Siddique, and J. Jiao, Editors. 2005, Springer: New York.
50. DeWeck, E.S.S. O., and D. Chang. Product Family and Platform Portfolio Optimization. in Proceedings of the 2003 ASME Design Engineering Technical Conferences – 15th International Conference on Design Theory and Methodology. 2003. Chicago, Illinois.

51. Simpson, T.W., Methods for Optimizing Product Platforms and Product Families, in *Product Platform and Product Family Design Methods and Application*, T.W. Simpson, Z. Siddique, and J. Jiao, Editors. 2005, Springer: New York.
52. Williams, C.B., *et al.*, Process Parameter Platform Design to Manage Workstation Capacity, in *Platform and Product Family Design Methods and Application*, T.W. Simpson, Z. Siddique, and J. Jiao, Editors. 2005, Springer: New York.
53. Stobaugh, R. and P. Telesio, Match Manufacturing Policies and Product Strategy. Harvard Business Review, 1983. 61: p. 113-120.
54. Park, B., S. Ghosh, and N.N. Murthy. A Framewok for Integrating Product Platform Development with Global Supply Chain Configuration. in National DSI Conference. 2000. Orlando, Florida.
55. Huang, G., X. Zhang, and L. Liang, Towards Integrated Optimal Configuration of Platform Products, manufacturing Processes, and Supply Chains. Journal of Operations Management, 2005. 23(3-4): p. 267-290.
56. Kim, B., *et al.*, Configuring a Manufacturing Firm's Supply Network with Multiple Suppliers. IIE Transactions, 2002. 34(8): p. 663-677.
57. Lai, X. and J.K. Gershenson. Representation of Similarity and Dependency for Assembly Modularity. in Proceedings of the 2004 ASME Design Engineering Technical Conferences - 18th International Conference on Design Theory and Methodology. 2006. Philadelphia, PA.
58. Guo, F. and J.K. Gershenson. Comparison of Modular Measurement Methods based on Consistency Analysis and Sensitivity Analysis. in Proceedings of the 2003 ASME Design Technical Conferences - 15th International Conference on Design Theory and Methodology. 2003. Chicago, Illinois.
59. Guo, F. and J.K. Gershenson. A Comparison of Modular Product Design Methods Based on Improvement and Iteration. in Proceedings of the 2004 ASME Design Engineering Technical Conferences - 16th International Conference on Design Theory and Methodology. 2004. Salt Lake City, Utah.
60. Stone, R.B., K.L. Wood, and R.H. Crawford, A Heuristic Method for Identifying Modules for Product Architectures. Design Studies, 2000. 21(1): p. 5-31.
61. Pimmler, T.U. and S.D. Eppinger. Integration Analysis of Product Decompositions. in Proceedings of the 1994 ASME Design Engineering Technical Conferences - 6th International Conference on Design Theory and Methodology. 1994. Minneapolis, Minnesota.
62. Paul, G. and W. Beitz, Engineering Design, A Systematic Approach. 1996, New York: Springer.
63. Chen, K. and R. Liu, Interface Strategies in Modular Product Innovation. Technovation, 2005. 25: p. 771–782.
64. Bettig, B. and J.K. Gershenson. Modular Interface Representation. in Proceedings of the 2006 ASME Design Engineering Technical Conference – 32nd Design Automation Conference. 2006. Philadelphia, Pennsylvania.