CONSTRUCTING A PRODUCT ARCHITECTURE STRATEGY AND EFFECTS (PASE) MATRIX FOR EVALUATION AND SELECTION OF PRODUCT ARCHITECTURES

Rice, Scott E. (1);
McKinnon, Samuel A. (1);
Sannar, Benjamin C. (1);
Mattson, Christopher A. (1);
Sorensen, Carl D. (1);
Anderson, Michael L. (2)

1: Brigham Young University;
2: United States Air Force Academy

ABSTRACT

Product architecture decisions are made early in the product development process and have far-reaching effects. Unless anticipated through experience or intuition, many of these effects may not be apparent until much later in the development process, making changes to the architecture costly in time, effort, and resources. Many researchers through the years have studied various elements of product architecture and their effects. By aggregating observations on the effects of architecture strategies from a selection of the literature on the topic and storing them in a systematic data set, this information can be recalled in a matrix structure which allows for the identification, comparison and evaluation, and then selection of the most desirable product architecture strategies before expending resources along any development path. This paper introduces this matrix, referred to as the Product Architecture Strategy and Effect (PASE) Matrix, how to construct one, and a demonstration of its use.

Keywords: Product architecture, Conceptual design, Early design phases, Design theory, Design process

Contact:
Rice, Scott E
Brigham Young University
United States of America
s_rice@byu.edu

Cite this article: Rice, S. E., McKinnon, S. A., Sannar, B. C., Mattson, C. A., Sorensen, C. D., Anderson, M. L. (2023) 'Constructing a Product Architecture Strategy and Effects (PASE) Matrix for Evaluation and Selection of Product Architectures', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.109

1 INTRODUCTION AND LITERATURE SURVEY

The scheme by which the function of a product is allocated to physical components (Ulrich, 1995) is known as *product architecture*. Architecture decisions are made in the early stages of the innovation process (Ulrich, 1995) when the product's basic functional units and the interfaces between them are chosen. In more formal product development processes, this occurs within the Concept Development Stage (Mattson and Sorensen, 2019). The product architecture chosen by designers often has consequences that may not be apparent until much later in the development process, when changing it is difficult or costly. Changes in the architecture also add significant effort in maintaining early documentation and model cohesion, specifically with digital twins (Jones et al., 2019). The effects of architecture decisions have been the subject of many researchers over the years. These efforts constitute a sizeable and valuable body of knowledge. From a selection of that body of knowledge, this paper seeks to create a more comprehensive and manageable way for designers to identify the link between product architecture strategies and the their effects, so that more meaningful architecture decisions can be made with downstream effects under consideration.

There are various product architecture strategies described in the literature, including the use of modular architectures. Authors such as Ulrich (1995) have discussed modular architecture and its impacts on development, while more recent work by Hackl et al. (2020) looks at the specific economic effects of modularity on a firm to create a network-dependency model. Brusoni et al. (2007) also looks heavily at modularity, with Farrell and Simpson (2003) examining those considerations in product platform designs. Sosa et al. (2000) compares modular with more integral systems. Other product architecture strategies for which choices must be made are discussed by Clark (1989) and Ulrich and Ellison (2005), on the use of custom, carry-over (previously designed in-house components), or commercial-off-the-shelf (COTS) components and their effects on project scope.

The amount of information available from all of the research on various product architecture strategies and their impacts is daunting in both its depth and breadth of scope. Nevertheless, a deep understanding of the literature is needed for designers to make use of this knowledge and improve their product development process. While experienced designers can often intuitively reduce risks and costs in their designs, this is restricted to efforts with which the designers are familiar. And because design is a complex endeavor involving individuals and teams often collaborating across organizational boundaries (Reich and Subrahmanian, 2022), it cannot be assumed or expected that all designers are either experienced or have engineering training. Thus it is difficult for many design teams to effectively leverage the existing information to improve their selections of architecture strategies and anticipate many of the effects of these selections.

This paper seeks to make insights gleaned from published findings more accessible by aggregating observations from the literature on product architecture, with a system for their storage and retrieval. This paper introduces the **Product Architecture Strategy and Effects (PASE) Matrix** as a new means for organizing this information and demonstrates how the use of this matrix can expand the designer's understanding of downstream effects of product architecture decisions.

The rest of this paper is organized as follows: Section 2 discusses the PASE Matrix and its formation, and section 3 describes the method used for gathering the data from the literature. Section 4 presents a demonstration of the PASE Matrix and section 5 contains the concluding remarks and discussion of potential future work in this area.

2 THEORETICAL DEVELOPMENT: PRODUCT ARCHITECTURE STRATEGIES AND EFFECTS MATRIX

This section introduces a new design matrix to facilitate the selection of product architecture strategies and the early identification of undesirable effects for mitigation.

2.1 PASE matrices and components

A review of the literature revealed that many product architecture decisions can be seen as architecture design strategies for achieving certain effects, such as on the product's performance and aspects of the design and production processes. Dozens of strategies and over 200 effects were identified from the literature surveyed. Arraying a selection of these strategies as rows, with their effects listed as columns,

https://doi.org/10.1017/pds.2023.109 Published online by Cambridge University Press

and the relationships between them indicated with an "X" at the intersections, a Product Architecture Strategies and Effects or PASE Matrix can be formed. The PASE Matrix enables designers to evaluate multiple product architecture strategies, systematically extract the implications of those strategies, and then select the strategies that are most desirable for use in their design project.
A meaningful evaluation of architecture strategies requires accurate knowledge of the strategies which can be used and their effects. The PASE Matrix makes clear the relationships that exist between strategies and their effects. This allows a thorough exploration and evaluation of all relevant architecture strategies which have been identified and documented from the surveyed literature. Strategies unknown to the designers are identified and considered along with those with which they are familiar, opening up more design opportunities. The PASE Matrix also ensures that all documented effects are taken into account for each strategy, eliminating the reliance on the memory or experience of designers. Figure 1 shows a representation of an Effects-Driven Approach PASE Matrix (see section 2.2) where some of the strategies and effects were intuitive to a designer, while others were not (See anticipated and unanticipated areas in Figure 1). The exact boundaries of these areas will vary depending on the designer and the matrix produced.

STRATEGIES OF INTEREST	EFFECTS OF INTEREST				RELATED EFFECTS									
	Effect A	Effect B	Effect C	Effect D	Effect E	Effect F	Effect G	Effect H	Effect I	Effect J	Effect K	Effect L	Effect M	Effect N
Strategy 1	X		x		X	X		X	X	X		X		X
Strategy 2		X				X	X						X	
Strategy 3			X	X						X	X		X	
Strategy 4	X	X					X					X		X
Strategy 5		X			X				X		X			

Anticipated Strategies & Effects:

Unanticipated Effects:

Unanticipated Strategies:

Figure 1. Anticipated and unanticipated strategies and effects

In order to build a PASE Matrix, a data set of strategies, their effects, and their relationships is required. Once a database has been established, there are two approaches to constructing the matrix. These approaches are described in the following subsections 2.2 and 2.3. A database was constructed to form the PASE Matrices used in the remainder of this paper. This database is stored in the form of rational tables and it is available at: https://www.design.byu.edu/resources/pasematrix.

2.2 Effects-driven approach

One approach that can be used to create a PASE Matrix for any design project begins with determining a set of effects which interest the design team, such as the effects on product testing and validation resulting from modular architecture decisions. This results in a PASE Matrix divided into the *effects of interest* and *related effects* that may have been unanticipated by the design team.

2.2.1 Steps for the effects-driven approach

1. Select Effects of Interest
   – Select effects from the available data set that are anticipated to be needed, probable to occur, or of possible concern for the designer's project.
   TIP: Organizing the effects into classes and sub-classes aids in organizing them for increased search efficiency. The database described in section 3 provides such an organization.
   TIP: Selecting too many classes or sub-classes of effects may cause the matrix to grow beyond a manageable size.

https://doi.org/10.1017/pds.2023.109 Published online by Cambridge University Press

	EFFECTS OF INTEREST				RELATED EFFECTS									
STRATEGIES OF INTEREST	Effect A	Effect B	Effect C	Effect D	Effect E	Effect F	Effect G	Effect H	Effect I	Effect J	Effect K	Effect L	Effect M	Effect N
Strategy 1	X		x		X	X		X	X	X		X		X
Strategy 2		X				X	X						X	
Strategy 3			X	X						X	X		X	
Strategy 4	X	X					X					X		X
Strategy 5		X			X				X		X			

Figure 2. Effect-driven PASE matrix

2. Identify Strategies and Related Effects
   - Identify all strategies related to the selected effects of interest (step 1), as shown by the relationships recorded in the database.
   - From these strategies, identify all other related effects.
3. Form a PASE Matrix
   - Create rows for the PASE Matrix from the identified strategies.
   - Create the columns by first listing the effects of interest, followed by a double line. The remaining related effects are then listed in columns to the right of the double line. A header for both "Effects of Interest" and the "Related Effects" is placed over each group to allow for easy distinction.
   - Indicate relationships between the various strategies and effects with an "X" at the appropriate intersections of rows and columns (See Figure 1) in accordance with the database.
4. Evaluate and Select Strategies
   - Consider each strategy and its set of effects, identifying the significant implications both positive and negative to the design effort.
   - Compare the strategies and their implications, selecting those which best achieve desired effects with the lowest cost in negative effects.
     TIP: Implications can be formed using the indicated relationships of the PASE Matrix, logical intuition, and designer experience.

This approach for constructing the PASE Matrix points the designer to strategies to achieve the selected effects of interest, and discovers other related effects that accompany those strategies.

2.3 Strategy-driven approach

A different approach for creating a PASE Matrix for any design effort begins with determining a set of architecture strategies of interest, such as the use of custom, carry-over, and COTS components. This will result in a PASE Matrix with a set of related effects that may have been unanticipated by the design team, as well as other strategies that may have similar effects at different costs.

2.3.1 Steps for the strategy-driven approach

1. Select Strategies of Interest
   - Select architecture strategies from the available data set which are anticipated to be needed, may be common practice in the industry, or are of interest to the design team for other reasons.
     TIP: Organizing the strategies into classes and sub-classes can increase search efficiency. The database described in section 3 provides such an organization.
     TIP: Selecting too many classes or sub-classes of strategies may cause the matrix to grow beyond a manageable size.
2. Identify Related Effects and Strategies
   - Identify all effects related to the selected strategies of interest as found in the database.
   - Next, identify all strategies that have a known relationship with the these effects.
   - From the new strategies, identify all of their related effects.
     TIP: While theoretically possible, and perhaps useful, it is not necessary to further identify additional related strategies and effects.

		RELATED EFFECTS													
		Effect A	Effect B	Effect C	Effect D	Effect E	Effect F	Effect G	Effect H	Effect I	Effect J	Effect K	Effect L	Effect M	Effect N
STRATEGIES OF INTEREST	Strategy 1	X		x		X	X		X	X	X		X		X
	Strategy 2		X				X	X						X	
	Strategy 3			X	X						X	X		X	
	Strategy 4	X	X					X					X		X
RELATED STRATEGIES	Strategy 5		X			X				X					X
	Strategy 6		X		X		X	X				X	X		
	Strategy 7	X		X		X			X	X				X	
	Strategy 8		X				X				X		X		X

Figure 3. Strategy-driven PASE matrix

3. Form a PASE Matrix
   - Create the top rows for the PASE Matrix from the strategies of interest, and the lower rows from the identified related strategies. Separate the two groups with a double line, and place headers before both the "Strategies of Interest" and "Related Strategies" groups easy distinction.
   - Create columns by listing all of the identified related effects.
   - Indicate Relationships between the various strategies and effects with an "X" at the appropriate intersections of rows and columns, in accordance with the database (See Figure 2).
4. Evaluate and Select Strategies
   - Consider each strategy and its set of effects, identifying the significant implications both positive and negative to the design effort.
   - Compare the strategies and their implications, selecting those which best achieve desired effects with the most acceptable cost in negative effects.
     TIP: Implications can be formed using the documented relationships of the PASE Matrix, logical intuition, and designer experience.

This approach for constructing the PASE Matrix gives the designer a comprehensive picture for the effects of the strategies they are considering for their design project. It also shows alternative strategies with which to achieve similar effects as the original strategies considered, broadening the designer's options as they evaluate which are the most beneficial strategies.

3 METHOD FOR DERIVING THE PRODUCT ARCHITECTURE STRATEGIES AND EFFECTS MATRIX

This section describes the method used for originally deriving the PASE Matrix from published findings on the effects of product architecture decisions.

3.1 Gathering observations

To construct a useful PASE matrix, a large database of strategies and their related effects organized in rational tables are required. A systematic literature review was performed to populate such a database for this paper. In the first step of the literature review, the influential articles *The Role of Product Architecture in the manufacturing firm* by Ulrich (1995) and *Impact of Modularity Decisions on a Firm's Economic Objectives* by Hackl et al. (2020) were selected, given their topical relevance and importance (Ulrich and Seering (1990) with over 4000 citations since 1995 and over 20 citations for Hackl et al. (2020) in less than two years). Additional papers were then reviewed that were either referenced by these two foundational papers, or cited them. An initial selection was made of those papers based on keywords pertaining to product architecture in the titles, resulting in a set of 199 papers. Next, the abstracts were reviewed, carefully reducing the set to 45 papers with greatest potential relevance. Finally, the bodies of the remaining articles were read, and categorized by which best explored key architectural decisions

https://doi.org/10.1017/pds.2023.109 Published online by Cambridge University Press

and their effects on downstream product development activities. This process ultimately identified nine papers for initial focus, along with the two source papers, to be thoroughly reviewed for this paper.
The reviewers recorded every reference to a cause-and-effect relationship relative to product architecture. After reading all the papers, they compared their records and consolidated duplicate observations. This resulted in 376 total observations, each given a unique identifier.

3.2 Organization and categorization of the data

It is unreasonable to expect a practicing designer to sort through all 376 observations and find the most-relevant information for their project. Thus, it became apparent that the database should be searchable by types of strategies and types of effects, and made interactive and accessible via a PASE matrix. To organize all of the observations by both strategy and effect, the KJ categorization method was used (Scupin, 1997). The KJ method is an abductive organizational method designed for categorizing observational or qualitative data sets (Scupin, 1997). Developed by Jiro Kawakito to make sense of data gathered during observational field studies in Anthropology, it has been adopted in a variety of fields open ended sets of data need to be organized.
Every observation from the 11 papers ((Ulrich, 1995; Hackl et al., 2020; Brusoni et al., 2007; Clark, 1989; Danese and Filippini, 2010; Eppner et al., 2018; Stone and Wood, 2000; Ulrich and Seering, 1990; Ulrich and Ellison, 1999, 2005; Wyatt et al., 2012) was sorted with other observations of a similar strategy. The observations were then re-sorted by similar effects. These became the basis for categorizing into classes the strategies and effects used in the PASE Matrix.
Once the strategies and effects were identified, they were all given unique identifiers with a letter code indicating type and then a three digit number. These were stored in corresponding rational tables, on each for strategies and effects. The relationships between strategies and effects describe the conditions for when a strategy could lead to a specific effect according to the observations. These details were recorded in the database in a Relationships Table. In the PASE matrix these relationships are only indicated by an “X”. Generally, these effects are not definitive or certain to occur, but dependent on how a strategy is implemented.
With several dozen strategies and two-hundred effects identified, a comprehensive PASE Matrix would be too large for practical use as there are hundreds and potentially thousands of relationships. Thus the database for the PASE Matrix is formed by five rational tables constructed by putting all like information in one table- such as the effects with their class and sub-class grouping information and their unique identifiers for each one. These are then linked to their corresponding strategies in the separate Relationships table. This eliminates needs for storing duplicate information and enables a query tool to be implemented for allowing designers to more easily access the information within the database.

4 PASE MATRIX DEMONSTRATION

In this section a demonstration of an Effects-Driven PASE Matrix is shown using real data gathered on strategies and effects. This demonstration assumes that a design team is following the steps listed in section 2.2.

1. Select Effects of Interest
   The design team surveys the list of effects from the database and identifies three of interest, as they are considered to be desirable in achieving some of the key customer needs or product requirements (See Figure 4).

ID	Effects of Interest
E-034	Increases product's Global Performance
E-046	Increases component Reliability & Maturity
E-050	Decreases mass in components

Figure 4. Effects the design team is interested in

https://doi.org/10.1017/pds.2023.109 Published online by Cambridge University Press

2. Identify Strategies and Related Effects
   Four product architecture strategies from the database are identified which can achieve the effects of interest (See Figure 5). These strategies are linked to nine other or related effects, as indicated by the literature (See Figure 6). (See Figure 6).

ID	Strategies of Interest
S-001	Using Commercial Off The Shelf (COTS) Components
S-002	Using Carry-Over Components
S-003	Using Custom Components
S-004	Using Function Sharing

Figure 5. Strategies that can yield the effects of interest

ID	Related Effects
E-001	Decreases Inventory Costs
E-017	Decreases development costs
E-018	Decreases production costs
E-024	Decreases development time
E-047	Decreases capital investment, ie. tools and people
E-048	Exploits economies of scale
E-055	Decreases product global performance
E-116	Increases tuning activities (in testing)
E-166	Increases need for new-to-firm capabilities

Figure 6. Related effects - effects linked to the strategies of interest, beyond the original effects of interest

3. Form a PASE Matrix
   A PASE Matrix relevant to the design team's interests is created using the information contained in Figures 4, 5, and 6. The matrix distinguishes between the effects of interest originally selected and the related effects which accompany the strategies of interest (See Figure 7).
4. Evaluate and Select Strategies
   The design team analyzes the information presented in the PASE Matrix, identifying the significant implications for each strategy, such as:
   – Using COTS and carry-over components can increase the reliability of components, but neither aid in increasing global performance, or decreasing mass. They can decrease costs and time, but COTS components may decrease the product's over-all or global performance.
   – Using custom components can aid in decreasing mass and increasing product performance, but not in increasing component reliability. It may also increase testing complexity and the need for new capabilities in the firm.
   – Using function sharing can increase reliability and decrease mass, while gaining some of the cost and time saving benefits as COTS and carry-over components.

After further deliberation, the design team decides that by developing custom components that use function sharing on the components with the greatest influence on mass and performance. The less critical components will be obtained from carry-over or COTS to increase over all reliability and decrease development and acquisition times.
Though not shown, the design team could also have developed a Strategy-Driven PASE Matrix (see section 2.3) which has a similar process.

https://doi.org/10.1017/pds.2023.109 Published online by Cambridge University Press

		Effects of Interest			Related Effects								
		E-034 Increases product global performance	E-046 Increases component Reliability & Maturity	E-050 Decreases mass	E-001 Decreases Inventory Costs	E-017 Decreases development costs	E-018 Decreases production costs	E-024 Decreases development time	E-047 Decreases capital investment, ie. tools and people	E-048 Exploits economies of scale	E-055 Decreases product global performance	E-116 Increases tuning activities during testing	E-166 Increases need for new-to-firm capabilities
Strategies of Interest	S-001 Using COTS Components		X		X	X	X	X		X	X		
	S-002 Using Carry-Over Components		X		X	X		X	X	X			
	S-003 Using Custom Components	X		X								X	X
	S-004 Using Function Sharing		X	X	X		X	X	X			X	X

Figure 7. Relevant effect-driven PASE matrix

5 CONCLUDING REMARKS

This section discusses the authors' findings, the potential utility of PASE matrices, and possible future work in this area of research.

5.1 Findings

Given that many early decisions regarding product architecture affect the downstream processes for the design team and the firm, this paper sought to delineate and codify these specific strategies and their relationships with effects as recorded in the literature. This can be done by filtering out specific, physical, and functionally relevant findings on product architecture from the body of literature. From these findings, a useful tool can be derived by distilling ordered lists of strategies, specific and measurable effects, and their relationships. The grouping of relationships becomes useful when implemented as a data table. The development of a PASE Matrix helps to make the data accessible and and more meaningful in individual cases. This method can be applied in many situations with the data collected here, or to a novel data set if organized similarly.

5.2 Utility

The PASE Matrix becomes a useful resource for validating the architecture strategies of a given design. Design teams may choose to validate a chosen product architecture by searching for the product architecture strategies it employs. Though it is possible that many of the effects the query will return have been anticipated by the designers, it was observed anecdotally that the matrix often returns effects that are not anticipated. These unanticipated effects may point to critical design issues that need to be addressed with a change to the product architecture, or with a shift in expectations for a product.

In a prototype activity developed for an undergraduate Senior Capstone Design course, the tool was useful for evaluating concepts under consideration. A PASE Matrix similar to that used in Figure 1 helped the students identify both positive and negative implications for some of the architecture strategies inherent in their concepts. This in turn allowed them to either gain confidence in a concept or consider changes to avoid the negative unanticipated effects.

5.3 Future work

This paper's data set is not comprehensive of all strategies and all of their possible effects. Work can be done to expand the reach, and thus utility, of the relationships table by conducting more and larger literature reviews. Implementing a text mining approach such as Topic Modelling (Chiarello et al., 2019) may alleviate some of the difficulties in locating and organizing many of the elements of product architecture that do fit easily within single categories.

Another area of interest would be human experiments to validate the utility of this table and to derive and to certify the most useful application of it. Some questions to be asked are: Can development time be saved using this table during ideation? Can unexpected delays be avoided by using this table to validate product architecture selection?

ACKNOWLEDGMENTS

We gratefully acknowledge the United States Air Force Academy for funding this research: Grant number FA7000-21-2-0007.

REFERENCES

Brusoni, S., Marengo, L., Prencipe, A. and Valente, M. (2007), "The value and costs of modularity: a problem-solving perspective", *European Management Review*, Vol. 4, pp. 121–132, http://doi.org/10.1057/palgrave.emr.1500079.

Chiarello, F., Melluso, N., Bonaccorsi, A. and Fantoni, G. (2019), "A text mining based map of engineering design: Topics and their trajectories over time", Vol. 2019-August, Cambridge University Press, pp. 2765–2774, http://doi.org/10.1017/dsi.2019.283.

Clark, K.B. (1989), "Project scope and project performance: the effect of parts strategy and supplier involvement on product development", http://doi.org/10.1287/mnsc.35.10.1247.

Danese, P. and Filippini, R. (2010), "Modularity and the impact on new product development time performance: Investigating the moderating effects of supplier involvement and interfunctional integration", *International Journal of Operations and Production Management*, Vol. 30, pp. 1191–1209, http://doi.org/10.1108/01443571011087387.

Eppner, C., Höfer, S., Jonschkowski, R., Martín-Martín, R., Sieverling, A., Wall, V. and Brock, O. (2018), "Four aspects of building robotic systems: lessons from the amazon picking challenge 2015", *Autonomous Robots*, Vol. 42, pp. 1459–1475, http://doi.org/10.1007/s10514-018-9761-2.

Farrell, R.S. and Simpson, T.W. (2003), "Product platform design to improve commonality in custom products", http://doi.org/10.1023/A:1027306704980.

Hackl, J., Krause, D., Otto, K., Windheim, M., Moon, S.K., Bursac, N. and Lachmayer, R. (2020), "Impact of modularity decisions on a firm's economic objectives", *Journal of Mechanical Design, Transactions of the ASME*, Vol. 142, http://doi.org/10.1115/1.4044914.

Jones, D.E., Snider, C., Kent, L. and Hicks, B. (2019), "Early stage digital twins for early stage engineering design", Vol. 2019-August, Cambridge University Press, pp. 2557–2566, http://doi.org/10.1017/dsi.2019.262.

Mattson, C.A. and Sorensen, C.D. (2019), *Product Development: Principles and Tools for Creating Desirable and Transferable Designs*, Springer Nature, http://doi.org/10.1007/978-3-030-14899-7.

Reich, Y. and Subrahmanian, E. (2022), "Documenting design research by structured multilevel analysis: supporting the diversity of the design research community of practice", *Design Science*, Vol. 8, http://doi.org/10.1017/dsj.2021.28.

Scupin, R. (1997), "The kj method: A technique for analyzing data derived from japanese ethnology", *Human organization*, Vol. 56 No. 2, pp. 233–237, http://doi.org/10.17730/humo.56.2.x335923511444655.

Sosa, M.E., Eppinger, S.D. and Rowles, C.M. (2000), "Designing modular and integrative systems", http://doi.org/10.1115/DETC2000/DTM-14571.

Stone, R.B. and Wood, K.L. (2000), "Development of a functional basis for design", http://doi.org/10.1115/DETC99/DTM-8765.

Ulrich, K.T. (1995), "The role of product architecture in the manufacturing firm", http://doi.org/10.1016/0048-7333(94)00775-3.

Ulrich, K.T. and Ellison, D.J. (1999), "Holistic customer requirements and the design-select decision", *Management Science*, Vol. 45, pp. 641–658, http://doi.org/10.1287/mnsc.45.5.641.

Ulrich, K.T. and Ellison, D.J. (2005), "Beyond make-buy: Internalization and integration of design and production", http://doi.org/10.1111/j.1937-5956.2005.tb00027.x.

Ulrich, K.T. and Seering, W.P. (1990), “Function sharing in mechanical design the concept of function sharing”, http://doi.org/10.1016/0142-694X(90)90041-A.

Wyatt, D.F., Wynn, D.C., Jarrett, J.P. and Clarkson, P.J. (2012), “Supporting product architecture design using computational design synthesis with network structure constraints”, *Research in Engineering Design*, Vol. 23, pp. 17–52, http://doi.org/10.1007/s00163-011-0112-y.