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14. ABSTRACT
In year two of a three-year project, progress is reported in all areas: support of ONR events, DSM research, interactions with leading researchers at conferences and meetings, and publications. Papers resulting from this work are also included.

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Design Structure Matrix, DSM, modularity, process modeling, ship design, design for adaptability, knowledge management

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Interim Research Progress Report—Year 2 of 3

Design Structure Matrix (DSM) Methods and Applications for Naval Ship Design

Grant # N00014-ll-l-0739

ATTN:
Ms. Kelly Cooper (code 333)
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ONR BAA 11-001:
Long Range Broad Agency Announcement for Navy and Marine Corps Science and Technology
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Prime (and Sole) Offeror: Texas Christian University

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Period of performance:
May 23, 2011 – May 22, 2014 (3 years)

Interim Research Progress Report—Year 2 of 3

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Accomplishments during the Second Year (May 26, 2012 to May 24, 2013)

The intention of this report is to provide a brief overview of key accomplishments during the second year. For further information regarding any item, please contact the principal investigator.

Support of meetings sponsored by ONR:

- Participated in planning discussions for upcoming NATO AVT-ET 132 Cost Working Group meeting, NSWCCD, July 8-9, 2013

DSM research:

- With help from a graduate student, continued survey and review of the state-of-the-art in DSM methods, including applications in systems engineering, engineering design, product development, organization design, process modeling, and project management.
  - Identified and acquired additional DSM articles
  - Further categorized hundreds of articles according to DSM application type, industry, and other criteria
  - Determined key insights in each application area
  - Next step: digest into literature review
- Worked with Navy personnel in Philadelphia on a DSM application to help design ship systems for adaptability, focusing on the case of a 400Hz power system (see below for related publication)
- Continued DSM research projects pertaining to software architecture and project management applications (see below for related publications; other papers in progress)

Interactions with leading researchers at conferences and meetings:

- Gave DSM tutorial at annual DSM conference (September, 2012) and served on the conference's program committee and as a session chair
- Gave DSM presentation at meeting of the European AMISA project[1] (in Modena, Italy, Dec. 2012): "Design Structure Matrix Models for Managing Project Complexity"
- Gave DSM presentations at the following venues:
  - University of Lugano, Switzerland, Dec. 2012
  - Institute for Operations Research and the Management Sciences (INFORMS) Analytics Conference, San Antonio, TX, Apr. 2013
- Attended Production and Operations Management Society (POMS) conference, Denver, Co, May 2013

DSM Publications:

- Bradshaw, Kristen A., Michael Robinson, Frank Scazzuso, Sean M. Gallagher, and Tyson Browning (2012) "Incorporating Modularity into Ship System Designs for Increased Adaptability," *Proceedings of the Maritime Systems and Technologies (MAST) Conference*, Malmö, Sweden, Sep 11-13.

[1] AMISA [Architecting Manufacturing Industries and Systems for Adaptability] is a 3-year, multi-million euro, research project funded by the European Commission in context of the 7^{th} Framework (Contract Number 262907). Companies and researchers from six countries—Germany, Israel, Italy, Romania, Spain, and Switzerland—are developing methodologies to design manufacturing industries and systems to be more adaptable to future needs (www.amisa.eu). Since its beginning in 2011, AMISA has used DSM as part of a new method for determining the types of investments that should be made early in a system design process to minimize the cost of its subsequent adaptability to unforeseen requirements. This project is normally closed to non-Europeans, but Dr. Browning has been invited to participate since the planned methodology is based on his past work (Engel & Browning 2008).

- Browning, Tyson R. and Steven D. Eppinger (2013) "Enfrentando a Complexidade de Projetos com Design Structure Matrix (DSM)" (in Portugese), *Mundo Project Management*, **9**(50): 54-60. (lead article)
- Browning, Tyson R. (2013) "Notes on the Design Structure Matrix," in Weiss, Stanley I., *Product and Systems Development: A Value Approach*, New York, NY: Wiley, pp. 213-218.
- Sosa, Manuel E., Jürgen Mihm, and Tyson R. Browning (2013) "Linking Product Architecture and Quality," *Manufacturing & Service Operations Management*, **15**(3): 473-491.

Incorporating Modularity into Ship System Designs for Increased Adaptability

Kristen A. Bradshaw[1], Michael Robinson[1], Frank Scazzuso[1], Sean M. Gallagher[1], and Tyson Browning[2]

Abstract

One of the most challenging issues in ship design is developing a system that meets the current, and future, needs of your customer. Failing to comprehensively define requirements often results in a costly and lengthy redesign effort that reduces the availability of the ship. Designing modularity into a system can lessen the impact of modifications to future mission requirements, because the system is more resilient and adaptable to change. Use of a Design Structure Matrix (DSM) allows one to investigate various system configurations with user defined metrics and requirements to quantitatively determine which components and/or systems should be modularized to increase total system adaptability.

The case study discussed in this paper explores the work done by the Naval Surface Warfare Center (NSWC) Philadelphia Machinery Research and Silencing Division, in coordination with Professor Tyson Browning of Texas Christian University. The work uses a DSM methodology to quantitatively measure the adaptability of a 400 Hz electrical system onboard a surface combatant.

Keywords *– modularity, adaptability, electrical system, Design Structure Matrix*

I. INTRODUCTION

Modularity is a core concept in design and innovation. It is highlighted as one of the twenty-seven tools in the Theory of Inventive Problem Solving (Altshuller 1996) and has a chapter in DoD5000.01 Directive, (DoD 1993). It is used in nearly every facet of our lives from the sections in this paper to the tetra package of your favorite beverage. Modularity is used in shipbuilding today; however, the application does not seem to deliver on the initial promise. For example, concept designs of the US Navy's Zumwalt Class Destroyer (Levedahl 1993), the US Navy's Littoral Combat Ship (GAO 2010), and MEKO concept of Blohm + Voss GmbH (MacKenzie 2006) have resulted in products that have failed to realize the real benefits of modularity. Instead, modularity is reduced to proprietary system designs, optimized for a single purpose, mindful of the future only by the use of margins. It has become evident that these margins alone are not enough to account for the impact of future ship system needs and capabilities.

A. Modular Open Systems Approach

The tendency to eschew modularity in design has led the United States Department of Defense (US DoD) to include modularity in its DoD5000.01 Directive, (DoD 1993), also known as the Modular Open Systems Approach (MOSA). MOSA highlights the benefits of designing modularity into a system. A key benefit is that a modular design can lessen the impact of modifications to future mission requirements, because the system is more resilient and adaptable to change. To aid in executing this directive, MOSA related documents provide three principles and tools for making sure a program is addressing modularity in its design. However, MOSA has been criticized for not providing "...a clear approach to determining how to implement Open Architecture in HM&E systems" (Alexander 2012). This is where the Design Structure Matrix tool can supplement the DoD5000.01 and provide a clear approach to modularity.

B. Design Structure Matrix

Use of the Design Structure Matrix (DSM) method, allows one to investigate various system configurations with user defined metrics and requirements to quantitatively determine which components and/or systems should be modularized to increase total system adaptability.

The Design Structure Matrix (DSM), also referred to as a Dependency Structure Matrix or Dependency Source Matrix, provides a compact representation of the relationships between elements of a system in a matrix format. A DSM is constructed by breaking down a system into its components. Each of these components is identified as both the rows and columns of the matrix such that the diagonal of the matrix is the intersection of the row and column of the same component. Each element of a matrix represents the interaction of two components of a system; a mark in a matrix element indicates that there is a connection between those two system components. The block diagram shown in the right portion of Figure 1, illustrates how each dependency (x) relates to each component.

Matrices can be constructed in one of two ways depending which way you are identifying forward process flow; either "across rows" or "down columns". We constructed our DSMs such that they read across rows, meaning that as one reads across a row, a marked cell will indicate a dependency of the row element on the column element. Representing a system as a matrix also allows certain mathematical algorithms to be performed that show how a system is organized. One such algorithm identifies groupings of design activities called a "cluster". A "cluster" of activities must be solved simultaneously, or the design activities must be re-sequenced. It is important to remember that iteration and rework are a necessary part of any design process; in fact strategically timed re-work may improve a process by increasing value

[1]Naval Surface Warfare Center, Carderock Division—Philadelphia; [2]Texas Christian University

and/or reducing cost and schedule. Thus it is both important to minimize unnecessary rework and manage the necessary rework. Necessary iteration can be managed in a number of ways: by tightening the feedback loop and minimizing the impact to other activities in the process (bringing a mark close to the diagonal in a DSM), splitting one activity into two such that one may address the rework without disturbing other activities, or even by combining several activities in order to have a similar affect.

The simple binary marks in some DSMs can be replaced by data such as the amount of potential re-work required or the probability of information change. This additional data can allow analysis of process failure modes and their effects on cost, schedule, and risk. System designers can get a sense of the flow of deliverables and where risks may be created (Browning).

We constructed our DSMs such that they read across rows, meaning that as one reads across a row, a marked cell will indicate a dependant relationship (dependency) of the row element on the column element, as shown in Figure 1. The block diagram shown in Figure 2, illustrates how each dependency (x) relates to each component in the more familiar flowchart graphical representation.

	Component 1	Component 2	Component 3	Component 4	Component 5	Component 6
Component 1			x			
Component 2	x					
Component 3		x				
Component 4		x			x	
Component 5	x					
Component 6			x	x		

Figure 1: Notional DSM Representation

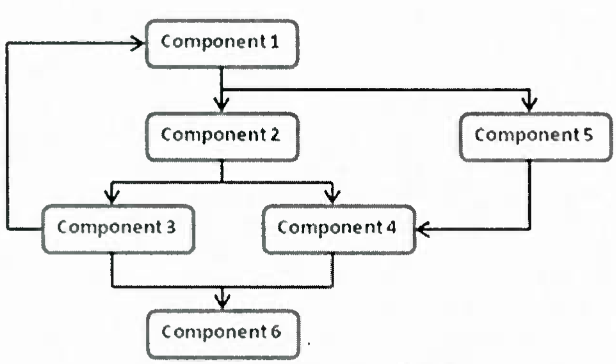

Figure 2: Notional Flow Chart

Representing a system as a matrix also allows certain mathematical algorithms to be performed that show how a system is organized. One such algorithm identifies groupings of design activities called a "cluster". These clusters can also be considered modules. Optimizing these modules for various characteristics can be done when the simple binary marks are replaced by data such as cost or the probability of information change. [Browning 2001]

II. APPLICATIONS OF MODULARITY

The majority of this paper's references extol the general benefits of modularity; lighter, smaller, easier to replace than the whole system. However, these are not the objectives targeted for this research to optimize modularity. The new paradigm will investigate reducing maintenance, standardization of interfaces and ease of technology upgrades.

Applying modularity as an optimization tool, the answer needs to be framed around questions such as 'How can modularity reduce maintenance?' and expand on the above answer, 'it makes it easier to replace'. Modularity provides a reduction in maintenance because, in a modular design optimized for maintenance, the components that have similar lifecycles are placed in the same module. Coordinating the replacement of these parts reduces maintenance time and equipment downtime. Furthermore, the need for interface standardization between modules permits new technology to be inserted more quickly. After all, part of maintaining a system is ensuring it does not become obsolete.

Modularity can be taken to varying degrees which amplifies the underlying question by Alexander (Alexander 2011), 'how can we quantitatively determine what we modularize and why?'. Attempts to answer that question have been made by several others. MacKenzie looks to how others have accomplished modularity, citing examples by Stanflex, MEKO, and Abeking & Rasmussen (MacKenzie 2006). In other cases, the solution of modularity is provided without quantitative justification. Levedahl suggests the solution to heavy, expensive and inefficient motor generators and solid state 60 Hz – 400Hz converters by recommending point of use conversion (Levedahl 1979), but does not provide a repeatable method for achieving optimal modularity. Optimizing the application of modularity requires a more robust approach than historical precedence or instinct.

III. CASE STUDY DISCUSSION

A. Objectives

The objective of the case study was to demonstrate the adaptability methods introduced by Tyson Browning on a distributed system, such as the 400 Hz electrical system, by performing matrix manipulation and cost analysis on a DSM of the system (Engel 2008). This case study will provide insight into a repeatable process applicable to future investigative studies.

B. Description and Assumptions

The paper presents a case study explored by the Naval Surface Warfare Center (NSWC) Philadelphia Machinery Research and Silencing Division, in coordination with Professor Tyson Browning of Texas Christian University, applying the DSM tool to quantitatively measure the adaptability of a 400 Hz electrical system onboard a notional surface combatant beginning its 30 year life.

The 400Hz system was selected in order to reduce the order of magnitude of the results for this initial study, while providing enough components to demonstrate the potential of DSM for use on any distributed system. The use of DSM for product design has already been demonstrated, (Tseng 2010 and Sharman 2007).

C. 400 Hz System

The 400 Hz electrical distribution system onboard a surface combatant provides power to weapon systems and special electronic equipment, as well as aircraft and landing craft. This distribution system is different from the 60 Hz electrical distribution system typically used on US Navy ships. The unique systems that use the 400Hz electrical power are using it as a means to reduce weight. Surface combatants are not as concerned about weight; therefore a cost benefit comparison typically results in a shipwide 60Hz electrical distribution system. However, the surface combatant also needs to supply 400Hz electrical power in order to support and interface with these unique systems, hence the need for a separate 400Hz system along with the 60Hz system.

D. Process

The first step in this case study was to determine how many different power supply options would be included. Historically, there have been three power supply evolutions of the system. Each used a different power source as its primary focus; a motor generator set, a solid state frequency converter, and a zonal power conversion module. Since each offered a unique product, all three different 400 Hz power distribution architectures were looked at in this study.

Next, subject matter experts (SMEs) answered a set of questions aimed at gathering the data necessary for the analysis. These questions were:

1. Identify system name and description; overview of key features, functions, and design issues
2. Determine a planning horizon
3. List of components, for each component:
    a. Component name
    b. SME
    c. Frequency or probability of change over the planning horizon due to its own intrinsic technologies or contents (not because of other components around it changing) (and rationale)
    d. Expected typical cost of changing the component (both redesign cost and procurement cost; include just the cost for this component-if other components would necessarily have to be redesigned also, then that should show up as change propagations)
4. Identify any existing or "natural" modules or subsystems of components. Are there any components that should not be together in a module because of procurement/acquisition reasons?
5. List of internal interfaces, for each interface:
    a. Name
    b. Type (spatial or flow of materials, information, or energy) (Sharman 2007)
    c. Probability of change propagation (and rationale), estimated cost to reduce this probability (even possibility to zero)
    d. How amenable is this interface to standardization? (qualitative data)
6. List of external interfaces
7. Update each component's probability of changing intrinsically to include any changes caused via external interfaces

Metric information was derived from the answers to these questions. Each metric probability had three discrete possible values of low, medium, and high. These probabilities capture the dynamic aspect of the system. For example, in the case of the probability of change propagation, it represents the probability that if there was a change in the component providing information in that dependency, how much propagation of that change would affect the receiving component over a 30 year lifecycle. For the probability of change, it represents the probability that the component will change over the 30 year lifecycle, whether it becomes obsolete, no longer is working, or a change in mission requirements that requires the component to be redesigned. The other two metrics that used the three discrete possible values were 'how amenable the interface is to standardization' and 'cost to reduce the probability of change propagation'.

The next few steps generated the initial DSM. The generic 400 Hz architectures were constructed into feasible architectures. These architectures were then decomposed into key components. The components were entered into a DSM, and the relationships between the components were established using the above mentioned generic architectures. At this point the DSM looked similar to Figure 1 with 'X' marks to signify that a relationship existed between the components. The next step is where the application of the DSM tool becomes unique.

In this step an interface table, using the headings shown in Table 1, was constructed with the metrics of the probability of change propagation, the probability of change with respect to components, and how amenable the interface is to standardization for each interface identified with an 'X'.

The resultant DSM in Figure 4 is a combination of surface combatant 400 Hz and 60 Hz power distribution systems technical, probability, and cost data. Since the 60 Hz system is an external interface to the 400 Hz system, it was included in the DSM for the study. The DSM includes information for all three architecture types. The individual architecture DSMs are broken out and described later on in this paper.

The next step is the application of a clustering analysis and the artifacts of the architecture options (AO). The DSM clustering technique is predicated on creating interconnect subsets of the components. The clustering is performed using the formula, (Engels 2008):

$$X = \alpha\left(\sum_{i=1}^{M} C_i^2\right) + \beta I \qquad (1)$$

where,

X is the expected economic value
α is the value added by modularizing
β is the value of interface development
C is the number of components in each module
I is the number of inter-module interfaces
M is the number of modules

Table 1: Metrics Documentation Chart Representation

Numbe	Unique Name	Type	Probability of Change Propagation (L,M,H)	Cost to Reduce the Probability (L,M,H)	Which Standard does it presently use	How amenable is the interface to standardization? (L, M, H)	Notes (Apply to Change Propagation Question)

400 HZ Electrical System		A 400 HZ Motor Generator Set	B 400 HZ Power Converter Module	C Frequency Converter Rectifier	D Frequency Converter Inverter	E Frequency Converter Local Control Panel	F 400 Hz Converter Maintenance Switch Box	G Bus Transfer	H AQB-A800 Bus Tie Breaker Connecting 400 Hz Switchboards	I 400 HZ Remote Control Panel	J 400 HZ Switchboard	K 400 HZ Air-Cooled Transformer (450Vac/120Vac)	L 400 HZ Power Panels	Environment (External Interfaces)
A	400 HZ Motor Generator Set	A												1S
B	400 HZ Power Converter Module		B											16
C	Frequency Converter Rectifier			C		1								17
D	Frequency Converter Inverter			2	D									
E	Frequency Converter Local Control Panel			3	4	E	S							
F	400 Hz Converter Maintenance Switch Box	6				7	F							
G	Bus Transfer	8				9		G						
H	AQB-A800 Bus Tie Breaker Connecting 400 Hz Switchboards							10	H	11				
I	400 HZ Remote Control Panel									I				
J	400 HZ Switchboard								12		J			
K	400 HZ Air-Cooled Transformer (450Vac/120Vac)										13	K		
L	400 HZ Power Panels											14	L	
	Environment (External Interfaces)		18				19						20	M

Figure 3: 400 Hz System Combined DSM

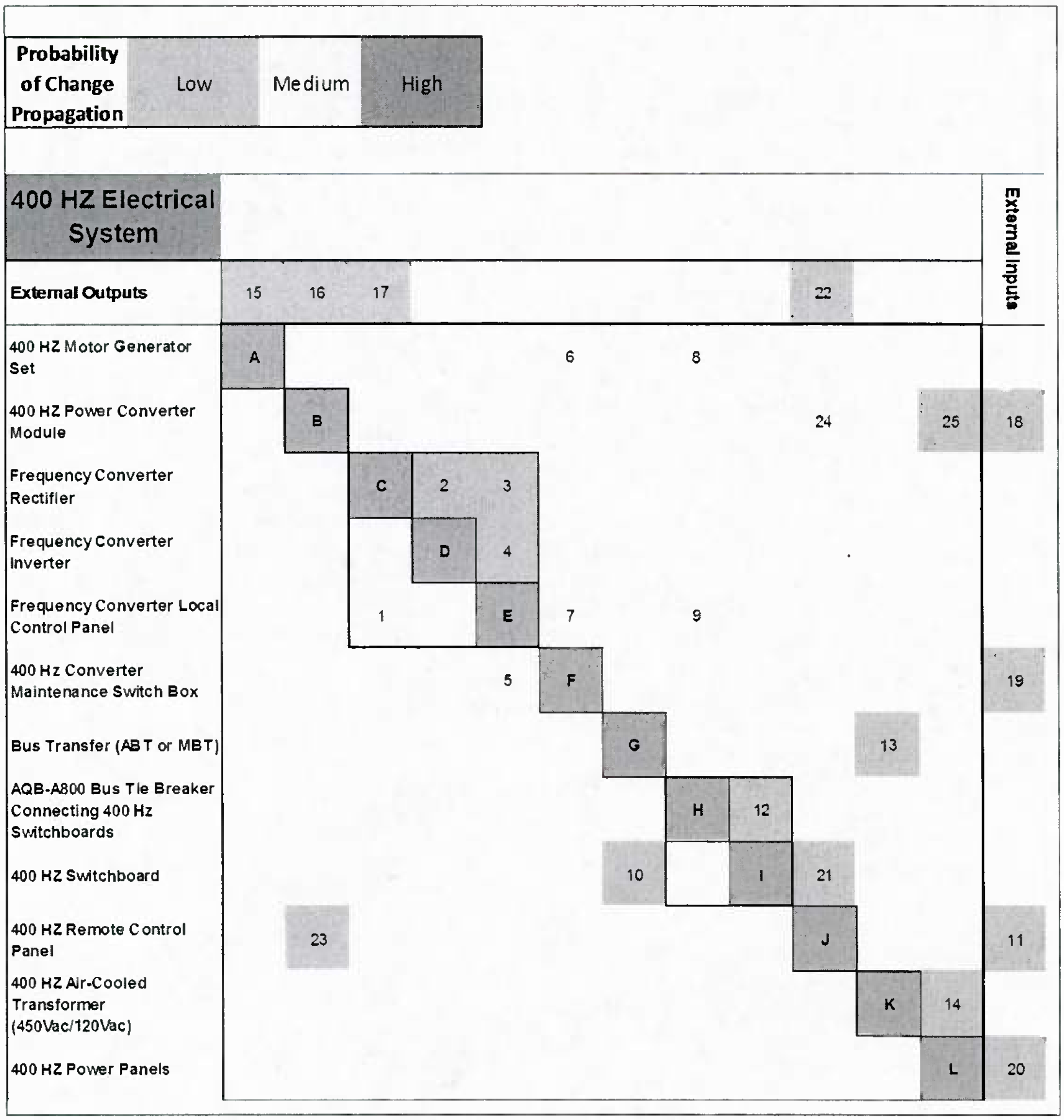

Figure 4: Initial DSM Clustering Analysis Results

The equation is then altered with elements of the real options theory to create the total value of the system (Engels 2008). The following formula results:

$$X_j^{(1)} = \sqrt{\sum_{n=1,2,\dots}(OV_n * SAF_n)^2} - \sum_{n=1,2,\dots}\left(\sum_{k=1,2,\dots} Ii_{n,k} + \sum_{l=1,2,\dots} Ie_{n,l}\right) \qquad (2)$$

where,

$X_j^{(1)}$ is the module value of the first architecture variant
OV_n is the option value
S is the component current value
AF_n is the weighted adaptability factor
$Ii_{n,k}$ is the internal interface cost factor
$Ie_{n,l}$ is the external interface cost factor

The formula for OV includes several key parameters: current stock price, strike price, volatility, time to expiration, and the risk free interest rate (Engels 2008). The current stock price was an SME's estimation of the current price of the equipment and the strike price was the current stock price including a maintenance cost of 5% per year. The Volatility was equated to the Probability of Change metric and the time to expiration was calculated at each of the following increments: 3, 5, 7, 10, 20 and 30 years. For this study, a Black Scholes Calculator (ref) was used to determine OV_n and the risk free interest rate were from Circular A-94 Appendix C (ref).

The adaptability factor (AF_n) used the Cost of Change of Component metric as a weighted value. The interface cost factors ($Ii_{n,k}$ and $Ie_{n,l}$) used the Probability of Change Propagation, Cost to Reduce Propagation and How Amenable is the Interface to Standardization metrics as weighted values. The interface cost factors were derived by summing the results of each weighted metric.

Once calculated using their respective formulas, each component received an associated option value and adaptability factor, while each interface received an interface cost. Equation 2 was then used to calculate the total value of each architecture based on the initial clustering of components and interfaces for each architecture. A high value, thus a high total system value for that 'time to expiration', is desirable, while a smaller value represents a lower system value.

IV. RESULTS

The final results of the analysis cannot be provided here due the propriety cost data. However, we will walk through a portion of the analysis to explain what is done with the formula.

In the first step in clustering a DSM for modularity, dynamic components are isolated from more stable components. When a component is expected to change over a planning horizon, it is said to be dynamic. In clustering, it is best to accept the least amount of change propagation through interfaces. This DSM is provided in Figure 5.

The cluster needs to be altered in this step, because even though the equipment may be considered dynamic, the cost to change the equipment may override the first step in the analysis. The DSMs in Figures 6, 7, and 8 show three different variations of the 400 Hz system, with accompanying text describing what would be recommended based on the initial clustering of components and interfaces. Each of the DSMs shown represents one of the many combinations of component and interface clusters.

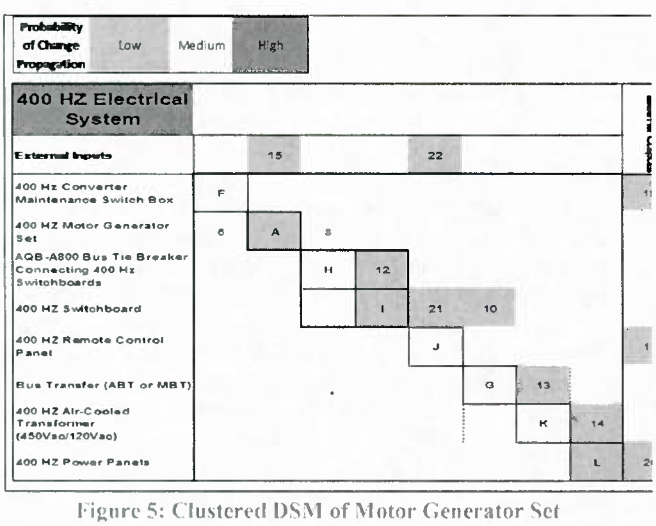

Figure 5: Clustered DSM of Motor Generator Set

The DSM in Figure 6 shows a 400 Hz system powered by a Motor Generator Set (Architecture 1). Through interpretation of the resulting DSM in combination with SME provided information, it has been determined that it would make the most sense to invest in a way to reduce the probability of change propagation across Interfaces 6 and 8. These two interfaces have the greatest effect on the Motor Generator Set, which is one of the most expensive piece of equipment. Also, Interface 8 has an impact on the Bus Tie Breaker, which is another expensive piece of equipment. If either, or both, of these interfaces were to change, it would result in an extensive cost impact to the system.

Combining Components H, I and J into a module seems logical based on the number of common interfaces; however, H is a magnitude more expensive than I and J. If H were to change, and HIJ was a module, it would be more expensive to change out the entire module. It can then be inferred that, typically, expensive components are better left isolated from less expensive components. Due to the shared interfaces between Components G and K, it is logical to combine them into a module. Further research is needed to investigate the benefits of creating a module containing components G and K based on the cost and interfaces between two components.

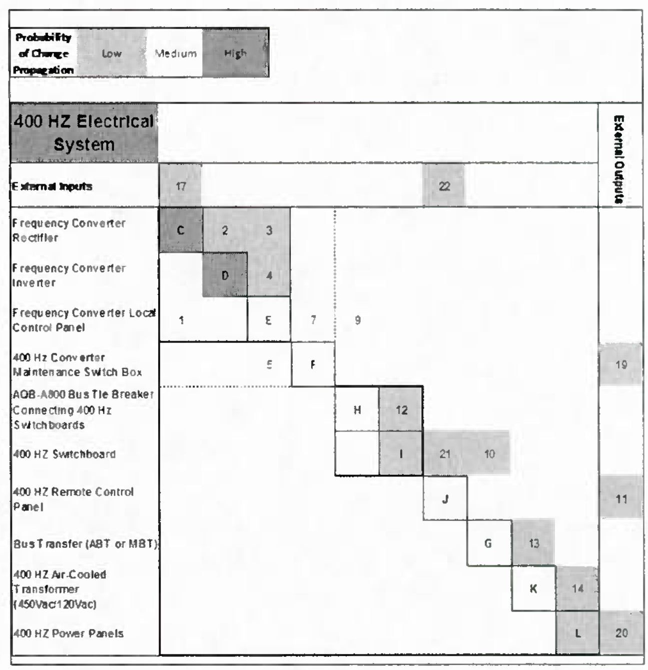

Figure 6: Clustered DSM of Solid State Frequency Converter

The DSM in Figure 7 shows a 400 Hz system powered by a Solid State Frequency Converter (Architecture 2). SME cost data shows that Components C, D, and E are relatively expensive and have similar probabilities of change propagation. Due to the number of like interfaces, it may be beneficial to modularize them. This would help to reduce the likelihood of change propagation across the interfaces. Taking a further look at the DSM, including Component F in the Module CDE may also help to reduce the likelihood of change propagation; however, further investigation of the other metrics needs to be explored. As in the Motor Generator Set DSM in Figure 6, Figure 7 clustering Components H, I and J seems natural to reduce propagation of change across their shared interfaces; however, the higher cost of Component H makes this module less desirable. Modularization of Components G and K will need further investigation to determine the associated benefits.

Probability of Change Propagation	Low	Medium	High	
400 HZ Electrical System				External Outputs
External Inputs	16	22		
400 HZ Power Converter Module	B	24	25	18
400 HZ Remote Control Panel	23	J		11
400 HZ Power Panels			L	20

Figure 7: Clustered DSM of PCM

The DSM in Figure 8 shows a 400 Hz system powered by a point of use Power Conversion Module (PCM) (Architecture 3). This is a relatively new technology that is still in the early design stages. This design eliminates the need for the intermediate components found in Architectures 1 and 3. This is done because the PCM is a point conversion approach, meaning that it directly interfaces with loads. This results in a much smaller DSM, with fewer interfaces. This PCM is a fairly expensive piece of equipment, so interfacing equipment should be changed first when the need exists. Conventional clustering would put B and J together in a module, but the AO approach suggests isolating the two components due to their high cost and probability of change propagation. As a result, steps should be take to standardize Interface 24 to make it less amenable to change propagation.

The final step is factoring in the cost impact of investing in the level of modularization in each architecture option. Calculation of the total system value for each of the three 400 Hz system architectures did not result as expected. It was found that regardless of the year the components or interfaces are replaced, the Solid State Frequency Converter had the highest value, followed not so closely by the Motor Generator Set. The PCM had the lowest value throughout the replacement years, which is contrary to logic. The PCM has the lowest number of components and was predicted by SMEs to have had the most total value. This discrepancy in total value is most likely due to a deficiency in Equation 2 in capturing the number of components in each architecture. Also, the magnitude of the interface cost factor was shown to be insignificant compared to option value numbers of four digits or more. Option values in this study were reduced by a factor of 100 in order for the interface cost to demonstrate an impact.

V. CONCLUSIONS

The case study in this paper demonstrates the viability of DSM to investigate various system configurations with user defined metrics and requirements to quantitatively determine which components and/or systems should be modularized to increase total system adaptability. Value estimation methodologies from the financial realm help to add another metric to the quantification of module development and interface specification. Thus, although additional work needs to be done to determine more accurate total system values, the application of DSM provides a clear approach to determining how to implement the Modular Open Systems Approach in mechanical and electrical systems.

VI. FUTURE WORK

Future work will include a more in depth investigation of the 400 Hz DSMs using the methods developed by Engels, Browning, Sharman Yassine, Baldwin and Clark to determine system value with respect to modular cost in the out years (Engels 2008, Sharman 2007 and Baldwin 2004). This research will include an investigation into the total value formulas to include a way to incorporate the number of architectures within a system and how the interface cost factor should be modified to more accurately impact a system. This investigation will be expanded to include multi-dimensional DSMs and their application to modularity and adaptability in shipboard systems. Larger distributed systems with more components and more interfaces, possibly the 60Hz electrical system, will be investigated once the smaller 400Hz scale studies are completed.

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VIII. BIOGRAPHIES

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RESOLVENDO PROBLEMAS DE **GERENCIAMENTO** DE **STAKEHOLDER** COM ABORDAGEM DE SISTEMAS **ADAPTATIVOS** A **COMPLEXIDADE**

John Findlay, Ph.D. e **Abby Straus**, M. Div.

IMPLEMENTANDO **FLEXIBILIDADE** COM **CONTINGÊNCIA** EM **CRONOGRAMA** DE **PROJETOS**

Homayoun Khamooshi, PhD.
Professor da George Washington University

ENFRENTANDO A COMPLEXIDADE DE PROJETOS COM

DESIGN STRUCTURE MATRIX

Dr. Tyson Browning - Professor Texas University ; **Dr. Steven Eppinger** - Professor MIT

PENSAMENTO SISTÊMICO HOLÍSTICO: UMA PRÁTICA ESSENCIAL EM PROJETOS DE LARGA ESCALA

Entrevista com **Dr. Mike Jackson** - Professor Emérito da Universidade de Hull (Reino Unido)

MPM PROJECT MANAGEMENT

Tackling Project Complexity with the Design Structure Matrix (DSM)

Tyson R. Browning and Steven D. Eppinger

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Many of today's major engineering projects are highly complex. They may involve hundreds of people doing thousands of activities to design and deliver a complex product, service, or system. The elements in such projects—product components, process activities, and organizational units—interact, often in surprising ways that cause the emergence of unanticipated behaviors. Although many project managers and participants understand this complexity, the profession still does not have adequate methods, models, and tools to manage complexity effectively. Lurking somewhere in the networks of product component interactions, process information flows, and personal communications are a subset of critical nodes and links that have major implications for project success. The trouble is, just which subsets are critical, and exactly when they need to be addressed, is elusive without an appropriate model to help visualize and analyze the situation.

Unfortunately, many of the most common models and views—such as Gantt (bar) charts, PERT (flow) charts, and work breakdown structures—do not provide sufficient richness to deal with these situations. Network models such as these often include only a minimal set of relationships among the elements (e.g., one arrow in and one arrow out), just enough to connect everything. However, if one actually asked those doing each activity what information they need to do their work (and do it right), they will usually list more than one item from more than one supplier. And they usually produce more than one result and send it to more than one place. Showing all this on a flowchart yields a mess of "spaghetti and meatballs" with many crossing lines, and modelers and users are quickly overwhelmed. So, there would seem to be a tradeoff between model richness and accuracy on one hand and model simplicity and usability on the other. However, a modeling approach called the design structure matrix (DSM) provides a way to get more of both of these capabilities, simplicity and completeness, at the same time.

Especially in design projects, which require accomplishing a set of dependent activities, information flow has critical implications. In manufacturing it is often impossible to do an activity without completing all of its predecessors. For example, two components cannot be assembled when one is not available. In engineering projects, however, most of the activities merely depend on *information* from predecessor (upstream) activities. If this information is not actually available, or if it is available only in preliminary or immature form, it is still possible to do the downstream activity based on *assumptions* about its missing or uncertain data. However, proceeding based on assumptions increases risk, because the finalized inputs, whenever they do arrive, could prove the assumptions invalid. Then the activity would have to do additional work (called rework) to clean up the mess. Even worse, if any problems with an activity's outputs are not found soon, or if those outputs change much later (e.g., because of rework), then this could cause a cascade of rework for other activities that had done their work based on what they thought were valid results from the reworking activity. Hence, the opportunity to begin an activity without all of its necessary inputs in place can afford advantages—in a macro sense it is what concurrent engineering is all about, as the design of a product and its production system overlap—but this degree of freedom is a double-edged sword, and it certainly makes managing a project more challenging. Actually, the most detrimental sources of rework can be pinpointed and avoided—if an effort is made to understand the information flow among project activities. Once again, the DSM provides the key.

What is the DSM? It is a square matrix where the cells along the diagonal represent the elements comprising a system and the off-diagonal cells represent the relationships among those elements. For example, the DSM on the left side of Figure 1 models eight elements, labeled A-H. The marks in the off-diagonal cells indicate a relationship directed from the element in column *i* to the element in row *j*. Thus, looking at column *i* shows the destinations of outputs from element *i*, and looking at row *j* reveals the sources of inputs to element *j*. For instance, element B provides outputs to elements D and E (as shown by the marks in column B), and it receives inputs from elements D, F, and G (as shown by the marks in row B). Hence, each diagonal cell can be both a provider and a receiver, and each off-diagonal mark is both an output and an input. These relationships can also be seen in the equivalent node-link diagram (or directed graph) shown on the right side of Figure 1. However, as the number of elements and relationships increases, the node-link diagram becomes increasingly challenging to visualize and understand. Meanwhile, note that the size of the DSM does not increase with the number of relationships among elements.

	A	B	C	D	E	F	G	H
A	A				X			
B		B		X		X	X	
C			C					X
D	X	X		D		X		
E		X			E			
F					X	F		
G			X				G	
H					X			H

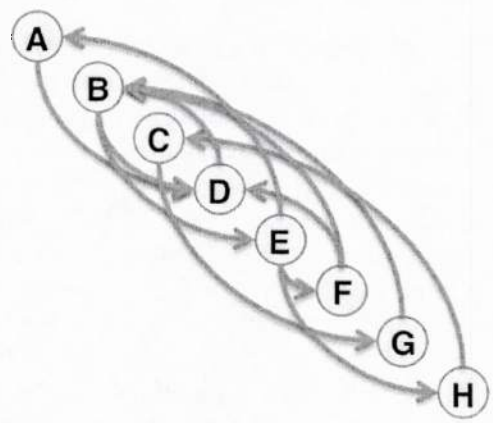


Figure 1: DSM and node-link diagram (directed graph) views of a system comprised of eight elements labeled A-H (images ©2012 MIT Press, used by permission).

DSMs come in two main types, static and temporal. Static DSMs represent systems where all of the elements exist simultaneously and the model captures a snapshot of the system in time. Static DSMs are often applied to product architectures, where all of the product's components exist at once to provide the system's functionality, and organization architectures, where all of the organizational units (e.g., people or teams) exist at once. Temporal DSMs add a time basis to depict systems where some of the elements exist or occur before or after other elements. Temporal DSMs are often used to model processes, where upstream activities occur before downstream ones.

DSMs have several advantages over alternative representations such as node-link diagrams and flowcharts. One is conciseness and ease of visualization, particularly as the number of elements increases. Another advantage is that a DSM lends itself to analyses that help reveal important patterns of interactions among the elements. Static DSMs are often analyzed using a technique called clustering, where the objective is to reorder the rows and columns of the DSM to assign elements to groups. These clusters may determine modules or other structures at higher levels of the system hierarchy. Temporal DSMs are often analyzed with an approach called sequencing, where an initial goal is often to minimize the instances of feedback in the system (marks above the diagonal in the DSM). This minimization of feedback marks in the DSM corresponds to sequencing the activities in a way that minimizes the number of assumptions they must make, thus lowering their risk of rework (with its cost and schedule implications).

In the remainder of this article, we focus on two examples of temporal DSMs used to model process architecture in product development projects. For further information on the DSM and these examples, as well as 42 others from various industries and countries, see the recent book *Design Structure Matrix Methods and Applications* by Steven D. Eppinger and Tyson R. Browning (MIT Press, 2012).

Example 1: Microprocessor Development Process at Intel

Figure 2 shows a DSM model of a product development process for a microprocessor at Intel. The process is modeled at the level of 60 activities, and the names of the activities are given to the left of the matrix. The rows and columns are numbered for easy cross-reference. "X" marks indicate planned information flows among the activities.

Figure 2 (on p. 5): Microprocessor development process at Intel (image ©2012 MIT Press, used by permission)

This DSM has been sequenced to represent the normal ordering and grouping of activities as executed by Intel. Many subsets of activities are connected in circuits of information flow, indicated in the figure by the blocks outlined along the diagonal of the DSM. These groups of activities are called interdependent or coupled, and their results must converge to a mutually satisfactory solution. This convergence often requires one or more iterations, which are expected and planned (although some uncertainty may exist about exactly how many iterations will be required and how long each will take). One benefit of the DSM is in helping to identify and highlight situations involving coupled activities, which require extra attention from project managers.

In addition to laying out the planned activities and information flow in the development process, this DSM also captures some organizational knowledge about ways the process could deviate from the ideal plan. Each of the "O" marks above the diagonal in the DSM represents a potential "failure mode" of the process, a place where information generated downstream is fed back and used to confirm the results of earlier work. If the earlier work is found to have flaws, then rework is generated. For example, activity 43, "Complete Product Validation" (marked with the red line in the figure) could fail to go as planned. If so, then one or more of five failure modes could trigger a return to one or more of five upstream activities for rework, even as far back as activity 17. (And rework of activity 17 could cause a cascade of rework throughout activities 17-28, which would again have to converge to a mutually acceptable solution, as well as activities 29-42.) These process failure modes were recognized as major drivers of project cost and schedule risk. Hence, the DSM can highlight potential rework loops that increase project risks.

Figure 2 also shows a few marks towards the upper-right of the DSM labeled "generational learning." These marks represent less significant process failure modes that would be too expensive or time-consuming to correct in the current project. They would require returning to the very first activities in the process and making changes that might ripple through too much other completed work. However, the organization wants to be sure it learns from these lessons in the next project, so it is noting these channels explicitly so that the next project will be sure to look at the results of activities 40 and 48 from the last project. Thus, the DSM can also serve as a basis for knowledge management, capturing an organization's hard-earned experiences and lessons about both planned and unplanned work and its results.

Example 2: Unmanned Aircraft Preliminary Design Process at Boeing

A DSM can also provide a basis for a process simulation. The DSMs at the top of Figure 3 show the 14 activities in the preliminary design phase of an unmanned combat aerial vehicle (UCAV) at Boeing. Instead of being a binary DSM, these numerical DSMs show the probability and impact, respectively, of a change in an activity's output. For example, the model shows a 20% chance of the output from activity 9 causing rework for activity 2 (row 2, column 9 in the left DSM), and, if this rework occurred, that 10% of activity 2 would have to be redone (row 2, column 9 in the right DSM). To the right of both DSMs is a table of duration, cost, and improvement curve (IC) information about each activity. The three cost and duration estimates represent the optimistic, most likely, and pessimistic outcomes, which were used to construct triangle distributions representing the probabilities of outcomes within these ranges. The IC factor represents any set-up or learning curve type benefits that would accrue on the second or subsequent workings of an activity. For example, building a simulation model might take a lot of work, but rerunning it with new inputs might take a fraction of this effort. For instance, if activity 2 must be completely reworked, this would require only 20% of its original time and cost. Some activities, such as activity 6, will take the same amount of time to redo as they took initially.

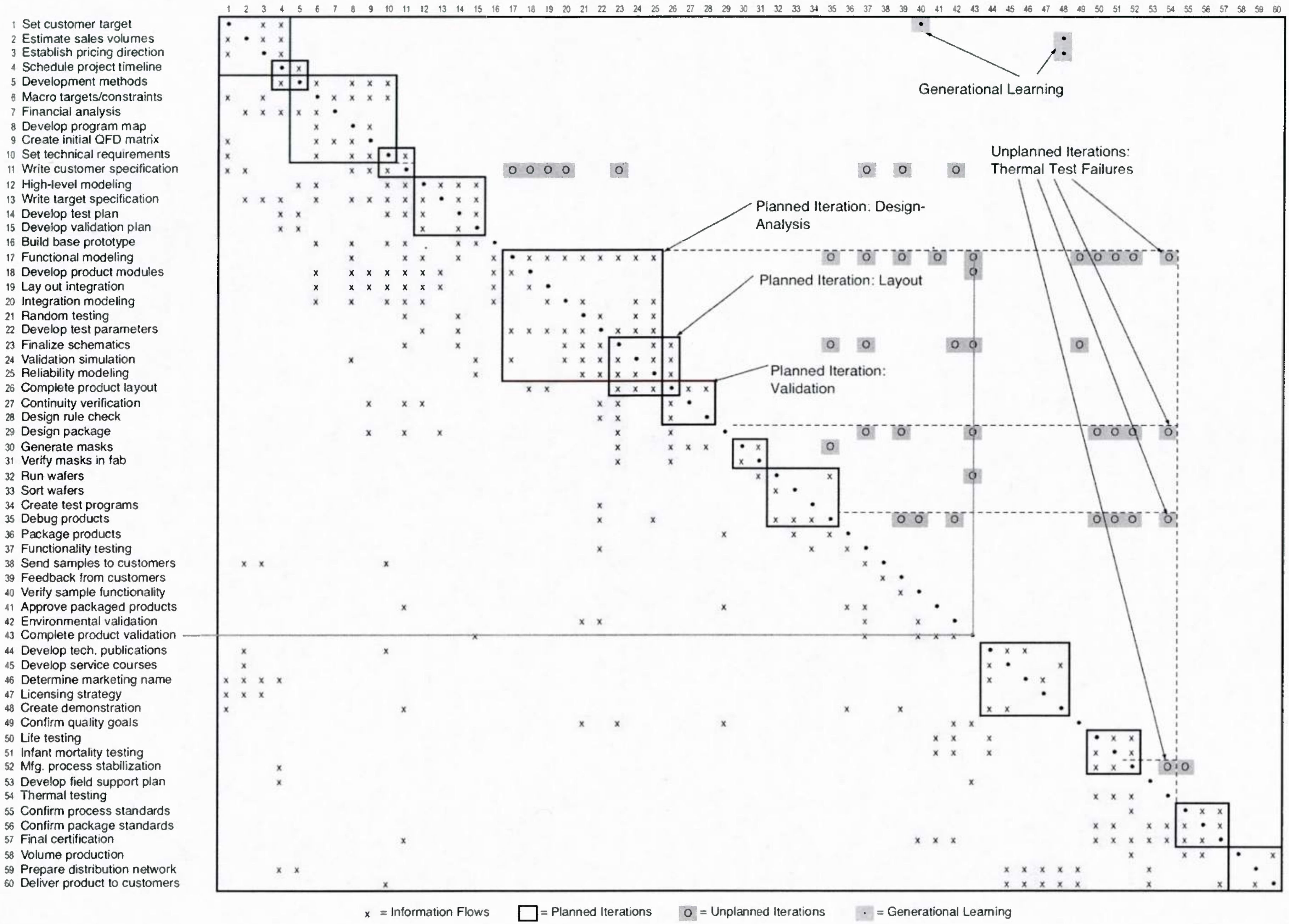
These inputs were used to simulate part of the UCAV development process. The middle of Figure 3 shows a Gantt chart from one run of the simulation. Unlike the typical Gantt chart, it shows rework appearing for activities 3, 4, 5, 8 and 9. This rework was not in the original plan, but it delays the project and increases its cost. Other runs of the simulation showed other occurrences and amounts of rework. Up to 1,400 runs were needed to achieve a stable distribution of cost and duration outcomes. These are plotted at the bottom of Figure 3, which shows a contour plot of the outcome frequencies (indicated by the shading). The deadline and budget are also shown, and project managers would like the outcomes to occur in the lower left, before the deadline and within budget. However, the simulation statistics indicate that 51% of the simulated outcomes exceed the budget and 67% miss the deadline.

This DSM model was also used to suggest some interesting process improvements and managerial options. For example, the top of Figure 4 shows a resequenced DSM with activity 13 moved upstream in the process. According to the Gantt chart in Figure 3, activity 13 is a rather long job on the critical path. By starting it earlier, based on additional assumptions, much of this work was able to be done off of the critical path. When the final information did arrive, it was likely to create critical path rework for activity 13. However, because the impact of this rework was light, and because activity 13 has a favorable IC, the rework took only a fraction of activity 13's full time and cost. The right side of Figure 4 shows the implications for the overall results. Although project cost increased slightly (increasing the portion of simulated outcomes that exceed the budget to 61%), its duration is decreased substantially (now only 7% of simulated outcomes miss the deadline).

Figure 5 provides some further insight into the effects of iterative overlapping, where the second activity in this figure represents activity 13 in the UCAV example. By starting activity 13 earlier, even without all of its required inputs, the risk of rework is increased, but with beneficial implications for project duration (at some minor added expense). The DSM simulation enables an analysis of all of these situations at once with many more than two activities involved. Note that iterative overlapping increases the number of feedback marks in the DSM, so it cannot be found using the basic DSM sequencing analysis of minimizing feedback marks.

Note also that the improvement in process duration in this example was achieved without any changes to the durations of individual activities. Whereas many process improvement approaches such as lean and six sigma often focus on improving individual activities (e.g., seeking to remove non-value-adding activities), taking a system view of the overall process can enable one to find leverage through changes to the process architecture—i.e., how activities relate to each other and work together based on the information they generate and use.

The DSM is ideal for exploring product, process, and organization architectures. Improved understanding of these can be a major key to innovative breakthroughs and competitive advantages.


1 Set customer target
2 Estimate sales volumes
3 Establish pricing direction
4 Schedule project timeline
5 Development methods
6 Macro targets/constraints
7 Financial analysis
8 Develop program map
9 Create initial QFD matrix
10 Set technical requirements
11 Write customer specification
12 High-level modeling
13 Write target specification
14 Develop test plan
15 Develop validation plan
16 Build base prototype
17 Functional modeling
18 Develop product modules
19 Lay out integration
20 Integration modeling
21 Random testing
22 Develop test parameters
23 Finalize schematics
24 Validation simulation
25 Reliability modeling
26 Complete product layout
27 Continuity verification
28 Design rule check
29 Design package
30 Generate masks
31 Verify masks in fab
32 Run wafers
33 Sort wafers
34 Create test programs
35 Debug products
36 Package products
37 Functionality testing
38 Send samples to customers
39 Feedback from customers
40 Verify sample functionality
41 Approve packaged products
42 Environmental validation
43 Complete product validation
44 Develop tech. publications
45 Develop service courses
46 Determine marketing name
47 Licensing strategy
48 Create demonstration
49 Confirm quality goals
50 Life testing
51 Infant mortality testing
52 Mfg. process stabilization
53 Develop field support plan
54 Thermal testing
55 Confirm process standards
56 Confirm package standards
57 Final certification
58 Volume production
59 Prepare distribution network
60 Deliver product to customers
Generational Learning
Unplanned Iterations: Thermal Test Failures
Planned Iteration: Design-Analysis
Planned Iteration: Layout
Planned Iteration: Validation
x = Information Flows
= Planned Iterations
O = Unplanned Iterations
= Generational Learning

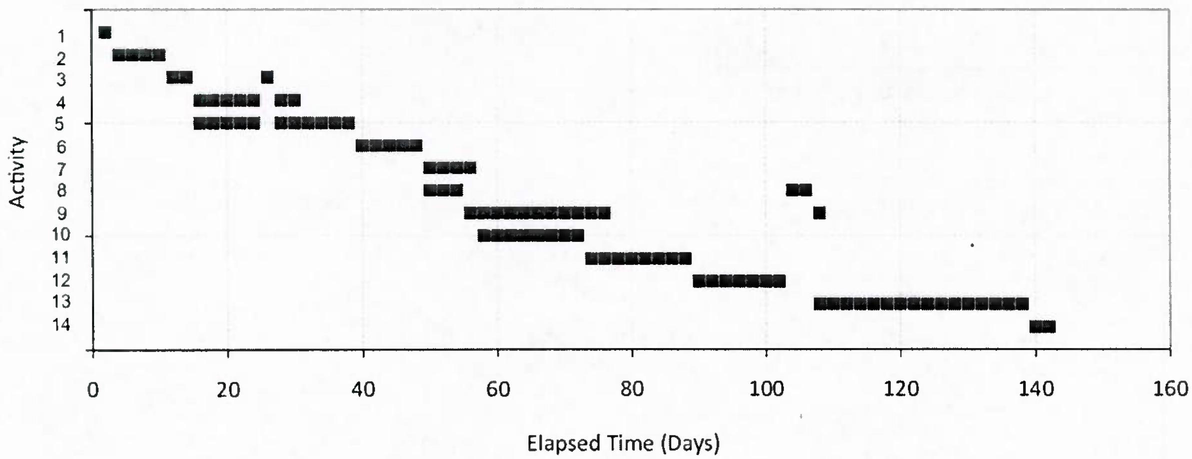
DSM Showing Rework *Probabilities*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1														
2	.4								.2					
3		.5		.4										
4	.3		.5											
5	.4		.5			.1		.1				.3	.1	
6	.1				.4									
7	.4					.4								
8						.5						.5		
9	.4		.5	.5				.5						
10				.1		.5	.2	.1			.4			
11						.5	.5	.5		.5				
12	.4					.4	.5			.5	.4			
13	.5				.5							.4		
14	.3	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	.4	

DSM Showing Rework *Impacts*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1														
2	.5								.1					
3		.3		.5										
4	.4		.8											
5	.1		.1			.1		.0				.3	.1	
6	.1				.3									
7	.5					.8								
8						.5						.5		
9	.3		.3	.3				.3						
10				.1		.5	.4	.3			.3			
11						.5	.5	.3		.3				
12	.5					.3	.5			.5	.5			
13	.9				.9							.3		
14	.5	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	.8	

Durations			Costs			
Min.	Likely	Max.	Min.	Likely	Max.	*IC*
1.9	2	3	8.6	9.0	13.5	35%
4.75	5	8.75	5.3	5.6	9.8	20%
2.66	2.8	4.2	3.0	3.2	4.7	60%
9	10	12.5	6.8	7.5	9.4	33%
14.25	15	26.25	128.3	135.0	236.3	40%
9	10	11	10.1	11.3	12.4	100%
7.2	8	10	10.8	12.0	15.0	35%
4.75	5	8.75	8.9	9.4	16.4	100%
18	20	22	20.3	22.5	24.8	25%
9.5	10	17.5	21.4	22.5	39.4	50%
14.25	15	26.25	21.4	22.5	39.4	75%
13.5	15	18.75	40.5	45.0	56.3	30%
30	32.5	36	213.8	231.6	256.5	28%
4.5	5	8.25	20.3	22.5	28.1	70%



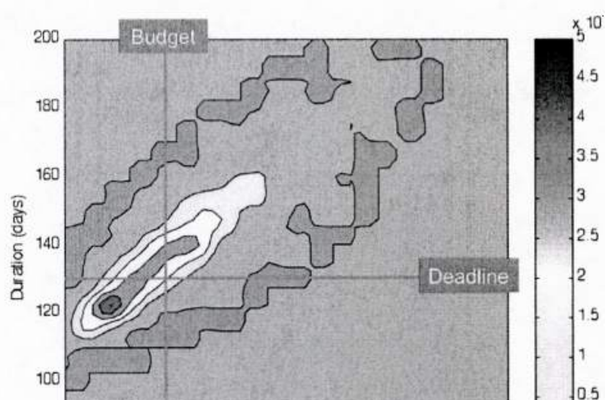


Figure 3: Data and initial simulation results for UAV preliminary design process (images ©2012 MIT Press, used by permission)

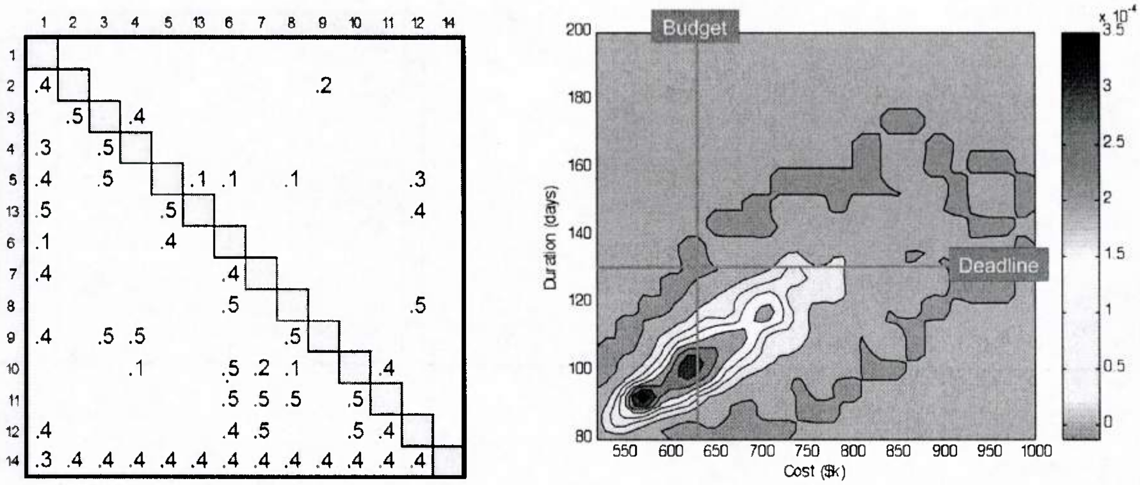


Figure 4: Alternative process with activity 13 moved upstream (images ©2012 MIT Press, used by permission)

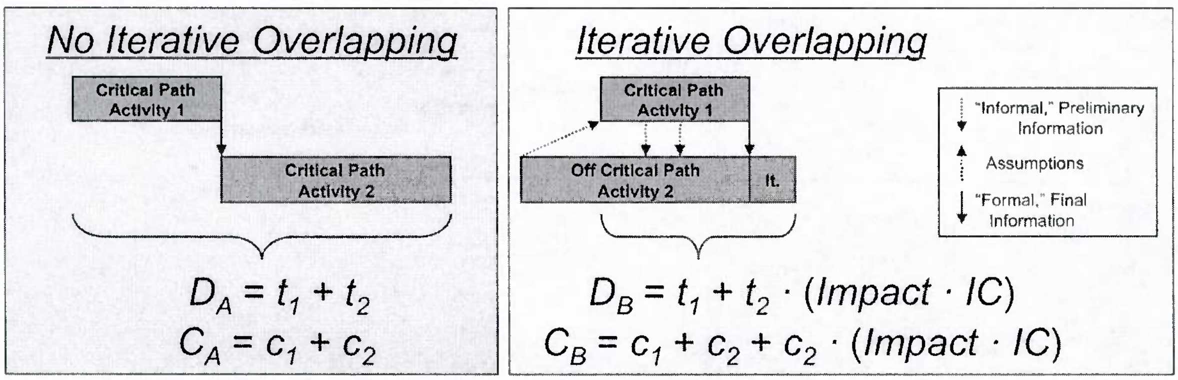


Figure 5: Illustration of iterative overlapping (images ©2012 MIT Press, used by permission)