Regular Paper

Technology Infusion for Complex Systems: A Framework and Case Study*

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ABSTRACT

Manufacturing companies in today's competitive environment constantly need to develop new technologies and infuse them into their line of products to stay ahead of the competition. Most new technologies only deliver value once they are successfully infused into a parent system. However, there has been little research done to develop formal methods to assess the impact of new technology infusion into existing products and systems. In this paper, a systematic framework to quantify and assess the impact of technology infusion early in the product planning cycle is proposed. The proposed methodology quantitatively estimates the impact of technology infusion through the use of a Design Structure Matrix (DSM) and the creation of a Delta DSM (ΔDSM) describing the changes to the original system due to the infused technology. The cost for technology infusion is then estimated from the ΔDSM, and the potential market impact of the technology is calculated based on customer value, expressed through utility curves for system technical performance measures. Finally, the probabilistic ΔNPV of a newly infused technology is obtained using Monte Carlo simulation. The proposed methodology was demonstrated on an actual complex printing system, represented as an 84 element DSM with a density of 3.7%, where a newly developed value-enhancing technology was infused into the existing product. The result shows that a positive marginal net present value ΔNPV can be expected, despite the new technology causing an invasiveness of 8.5% to the existing design. The methodology can be applied in a rigorous and repeatable manner, opening up possibilities for further implementation of the proposed framework, including analysis of the interactions amongst multiple technologies.Syst Eng 13: 186–203, 2010

Key words: technology infusion, system integration, incremental innovation, DSM, NPV, product value

1. INTRODUCTION

Most products are not clean sheet designs but evolve from earlier products. This is true in many industries that are based on electromechanical and software technologies. The reasons for this are that the time and effort to design products "from the ground up" is often prohibitive and that important lessons learned from earlier generations of products may be lost due to *de novo* design.

One form of product evolution is the *infusion of new technologies* into existing products and product platforms.

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Such innovations can be based on individual components, but are generally larger in terms of scope and their impact on the underlying product architecture and functionality [Henderson and Clark, 1990]. Typically, new technologies are developed as prototypes "in the laboratory," where they are gradually matured. Once a certain level of maturity has been reached, the candidate technologies are proposed for infusion and then need to be assessed in terms of their potential "invasiveness" and anticipated effort associated with integrating them into their host product(s) [Tahan and Ben-Asher, 2008]. Moreover, the potential value (due to such a technology infusion/upgrade) they may bring to the firm in terms of increased sales, market share, and ultimately profit needs to be estimated. Potential value to stakeholders can be estimated using many methodologies and/or metrics available, including real options [de Neufville, 2003], product value estimation [Cook, 1997], and architecture option evaluation [Engel and Browning, 2008], just to name a few. Often more alternatives and options exist than can be acted upon. To manage the portfolio of technology investments, one would like to position different technologies in terms of both their level of invasiveness and associated risk, as well as their expected value to the firm relative to each other.

In Figure 1 technology A is easy to implement, but only represents a small improvement. Technology B is attractive since a significant return can be expected with moderate investment. Technology C promises the largest expected value but is also the most invasive and risky. Technology D appears to be unattractive because it is relatively invasive but provides only modest incremental value.

In the Technology Infusion Analysis (TIA) method described here we define *value* monetarily as "net present value." This is computed as the discounted net cash flow of all products that carry the technology under investigation. Performing such an assessment is a challenging task and requires prioritizing and rationalizing technology infusion based on a consistent methodology and quantitative metrics. Since large investments in human resources and money are often required (on the order of person-years and $ millions), technologies should not be located in Figure 1 through a purely qualitative exercise based on intuition and "experience" alone, but should be based on rigorous and quantitative technical and financial analysis.

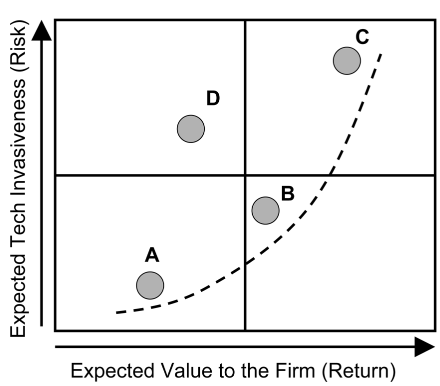

Figure 1. Risk versus return of technologies.

This paper addresses this challenge by developing and demonstrating a Technology Infusion Analysis process. This paper states the explicit goals of the research, surveys the literature on technology infusion, proposes a new technology infusion analysis process, and demonstrates this process for a real industrial application through a case study. The lessons learned and challenges encountered during the course of the research are discussed following the case study results. It must be noted that the proposed Technology Infusion Analysis process is primarily aimed at assessing the impact of incremental innovations, which are more frequent throughout industry, rather than truly disruptive innovations, which occur with far less frequency. Also, the proposed process aims to provide a means to pinpoint the questions that subject matter experts in each subsystem will assess in their respective areas. Finally, the proposed process does not address the robustness of the infused technologies. Rather, it helps to identify components and interfaces that need to be implemented to achieve the desired functionality.

2. PROBLEM STATEMENT

The overall goal of the research is to develop a formal capability for conducting technology infusion analysis, according to the following problem statement:

> Problem Statement: Develop and demonstrate a framework and method for quantitatively assessing the impact of infusing a new technology into existing or future product architectures. The method should be clearly described and easy to implement and should capture technical as well as market and financial impacts of a technology, including the uncertainty of the expected impact. A toolset and prescription for repeatable implementation of technology infusion analysis should support the framework and method.

The *approach* taken in this research is summarized below:

1. Problem definition and scope
   a. Document existing practices for assessing technologies
   b. Define a relevant products/systems platform to study
   c. Define the technology to be considered.
2. Attempt to apply an existing technology infusion method [Smaling and de Weck, 2007]. Modify the method as needed.
   a. For the chosen products/system, perform baseline DSM[1] construction
   b. Construct a [2]ΔDSM for the chosen technology
   c. Quantify technology invasiveness and effort
   d. Quantify technology benefit
   e. Perform uncertainty analysis.

[1]The Design Structure Matrix (DSM) is a matrix that maps components to components by showing their interconnections. DSM is an increasingly popular method to assist with system design, see [Eppinger et al., 1994].

[2]A ΔDSM captures the "changes only" that are necessary to infuse a technology in a host product.

With rapid implementation of this formalized process, the expectation is that more rigorous and quantitative evaluation of technology infusion will be possible, complementing existing processes for better decision-making.

3. LITERATURE REVIEW AND GAP ANALYSIS

3.1. Literature Review

There is an abundant literature on the role that new technologies have had in creating new industries, but also in disrupting existing ones. This is typically referred to as "industry dynamics" [Utterback, 1996] due to innovation. A helpful distinction is that between component technology innovation and architectural innovation [Henderson and Clark, 1990]. Much attention has been paid to so-called "disruptive technologies" [Christensen, 1997], which have the ability to render entire families of products and entire industries obsolete. This certainly occurs, but a much more prevalent case is that technologies are used to *gradually evolve* existing products and to make them better with each generation.

A specific example can be found in Downen [2005], where the impact of the introduction of jet engines in business aircraft was quantified. Figure 2 shows the relative value index versus price of different business aircraft in 1970, around the time when small business jets were first introduced. Relative value in this case is a weighted index[3] comprising three functional attributes that together quantify the value of an aircraft: maximum speed, cabin volume per passenger, and available seat-miles.

It can be seen how the midsize jets clearly dominate heavy turboprops of equivalent size. Indeed, after 1970 business jets gradually displaced the heavier and slower turboprop aircraft in this market segment. The new technology caused a shift in the achievable efficient (Pareto) frontier. It did not displace business aircraft altogether. The main challenge was in how to scale down engines from larger aircraft and how to integrate them efficiently into airframes for aircraft carrying on the order of 10 passengers.

Previous research [Smaling, 2005] has established a framework for systematically identifying and quantifying the risks and opportunities for infusing a single new technology into an existing system or product. This was previously applied to hydrogen-enhanced internal combustion engines [Smaling and de Weck, 2007]. This technology infusion analysis framework is shown in Figure 3.

In this framework, first, a baseline model is made of the existing host system/product using the Design Structure Matrix (DSM) technique [Eppinger et al., 1994]. The DSM is essentially a "map" of the system and its product architecture. In the DSM the rows and columns correspond to hardware and software components of the system, while the cells show the interconnections between the components. DSM is widely used to investigate system decomposition and integration problems, guiding decision makers to cluster and partition system architecture, organization, and map the action sequence for sets of activities and system parameter execution [Browning, 2001, 2002].

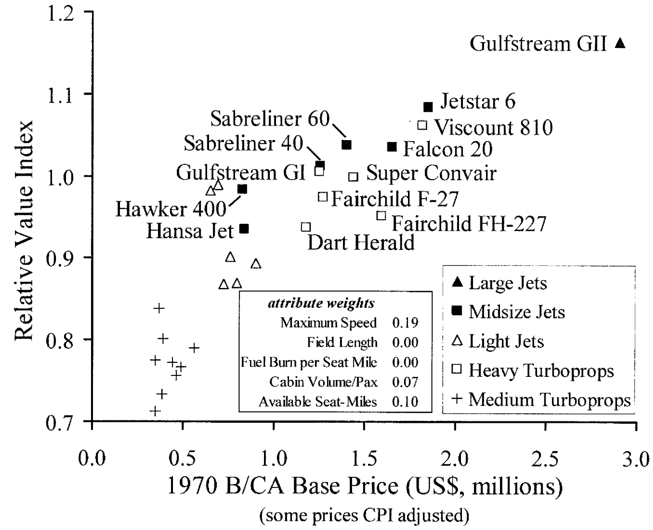

Figure 2. Relative value index versus base price for business aircraft in 1970 [Downen, 2005].

Different concepts, C1, C2, …, CN for infusing a technology into the underlying product architecture are developed and their performance and cost impact is estimated through simulation. Rather than a single point estimate, Monte-Carlo simulation (step 1) is performed across a range of design instantiations, represented by their design vector **x**, to obtain an estimate of the variability in performance and cost for each concept (step 1). Because of the large amount of data this step generates in the objective space (*f*), two levels of filtering are applied to the data to arrive at a more manageable set.

In step 2 (Fuzzy Pareto Filtering), the preferred technology concepts are identified. However, because of the remaining uncertainties, both nondominated ("Pareto optimal") and promising dominated designs are chosen. A fuzzy Pareto filter allows retaining apparently dominated designs as a function of the slack parameter *K*. Next, in step 3, design-domain linked filtering is applied on the reduced Pareto set. This means that only solutions are eliminated that are close to each other *both* in the design space and in the objective space. Designs (with the new technology) that achieve the same level of performance, but do so in a very different way in the (physical) design space should be retained. This leads to a reduced set of alternatives for further consideration.

The upper path in Figure 3 serves to quantify the level of Technology Invasiveness (TI) of each technology concept C1, C2, …, CN. The main idea here is the *Delta-DSM* (ΔDSM) that captures the architectural invasiveness of a technology to its underlying host system/product. This is done by carefully recording the actual or expected changes that need to be made to the underlying system/product—as represented by its underlying baseline DSM—in order to infuse each technology concept. The types of changes will be discussed in detail below. The total number of changes is then used to arrive at a weighted technology invasiveness index (TI). The larger the

[3] Referred to by Downen [2005] as the Relative Value Index (RVI).

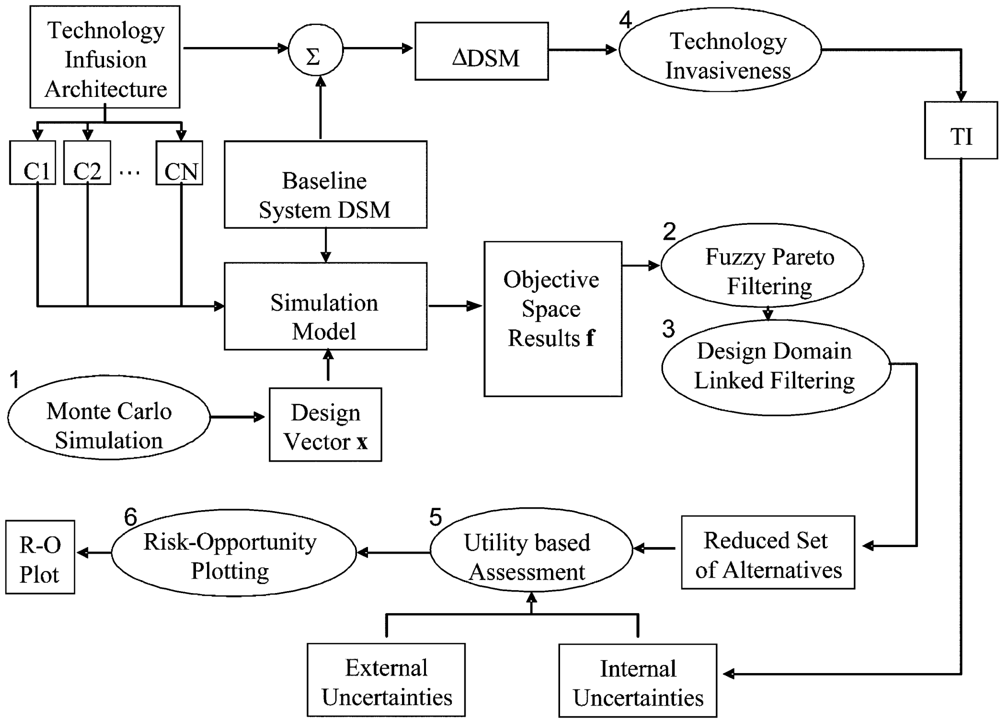

Figure 3. Technology risk-opportunity framework [Smaling, 2005].

TI, the more work is required and the riskier the technology integration project is likely to be.

The fifth step in Figure 3 is a utility assessment where the performance measures of each technology are mapped to a utility function between 0 and 1. The internal uncertainties that are considered are the ability to achieve a certain technology performance target, as well as technology invasiveness, TI. The external uncertainties are embodied in a set of "scenarios" which reflect a set of different futures that may occur and that may positively or negatively affect the value of the technology under consideration. This is then used to compute a level of risk and opportunity for each technology infusion concept, which can then be plotted for decision-making (step 6.) Each technology infusion concept then appears as a polygon (one vertex for each scenario) in a Risk-Opportunity chart.

3.2. Literature Gap Analysis

After publication and application of the technology infusion framework [Smaling, 2005; Smaling and de Weck, 2007], a number of critiques and suggestions for improvement were raised. These are summarized below:

- Guidelines are needed for consistent construction of a baseline DSM. Particular attention needs to be paid to the degree of abstraction of the DSM when rows and columns represent more than atomic parts/components. As results of the research presented in this paper, a detailed guideline for consistent DSM construction has been documented.
- The way in which asymmetrical entries in the ΔDSM are handled is somewhat ambiguous. It is clear that changes on the main diagonal of the ΔDSM represent component/subsystem changes, and off-diagonal changes can be interpreted as interface changes. For flows that are allowed to be asymmetrical (mass, energy, information), do we either count both sides of the interface or only one side when changes are necessary?
- The values of the Technology Invasiveness index are not very helpful except in a relative sense. It may be helpful to normalize the TI against the underlying baseline DSM and/or to use the TI to estimate actual change effort (either in person-years or in monetary units).
- The utility assessment using piecewise linear utility curves, ultimately leading to a measure of risk and opportunity, is helpful but offers many opportunities for somewhat arbitrary weighting factors and subjective adjustments that may influence the risk-opportunity positioning of a particular technology or technology infusion concept. It may be more helpful to quantify the expected net present value (NPV) or return on investment (ROI) of a technology infusion project. This would require modeling the impact that a technology may have in the market place in terms of sales and profitability impact on the host product. This paper attempts to connect the efforts of technology infusion, estimated by DSM and ΔDSM, to traditional NPV and ROI estimation.
- Adjustments of the method may be required depending on the context in which it is used.

Based on these suggestions, an improved technology infusion assessment framework was developed and is presented in the following section.

4. PROPOSED TECHNOLOGY INFUSION FRAMEWORK

4.1. Framework Overview

This section describes an adaptation of the technology infusion analysis process described above [Smaling and de Weck 2007] with implementation of suggested improvements. Its intent is to address some of the deficiencies discussed in the earlier section. One of the primary areas of focused improvement is assessing value in terms of dollars vs. an arbitrary relative scale.

The usual value proposition for product development is described below, based on the framework provided by Cook [1997]:

- *Companies:* Create profit by selling products at a price above its manufactured cost.
- *Customers:* Purchase a product at a given price, when they believe that it will add "value" expressed in terms of monetary value ($) that exceeds the price paid.
- *Value* of a product is realized by its price, its market share among competitors, and its customer preferred attributes.

There are different ways in which the overall value available to customers can be affected. A nominal view of value to product manufacturer vs. customer is shown in Figure 4, column A. One way to improve customer value is to reduce product manufacturing cost and to pass on those savings by reducing prices [(hopefully while maintaining margins (manufacturing value B >= manufacturing value A)]). Another approach is to continuously innovate and to develop new architectures and technologies that will improve products from one generation to the next, increasing the overall value of the product to customers (customer value C > customer value B). This gives the manufacturer the potential flexibility to increase margins and customer value simultaneously (as long as the realizable customer value increase exceeds any increase in cost to manufacture and support the product). Many firms today need to work both paths (B) and (C). The balance of this report focuses on developing alternatives along path (C).

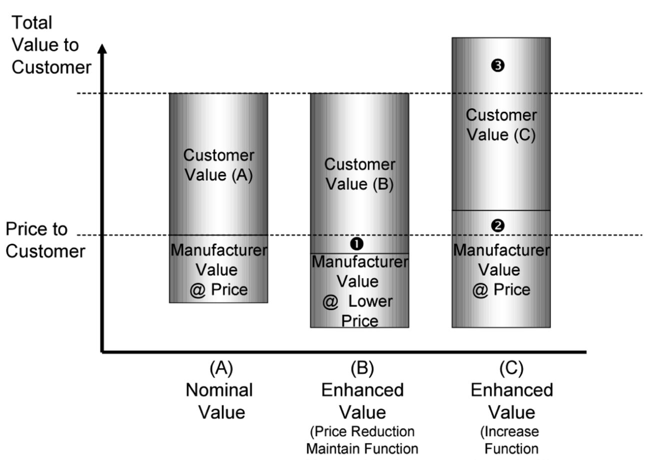

Figure 4. A nominal view of value to manufacturer vs. customers.

Firms develop new technologies and then infuse these into new products. Not all technologies will be successfully infused into products. One possible approach is to allow some technologies to fail early. However, a methodology is needed to increase the likelihood of identifying "winning" technologies [Schulz et al., 2000] that are likely to be successful and to help prioritize between those viable alternatives if all cannot be pursed.

Infusion of new technology has the potential to add value, but we need to capture the following main aspects before making specific decisions about individual technologies:

- Effort and uncertainty associated with technology development and infusion into a host product or platform.
- Effect that the technology has on the product functional attributes and manufacturing cost.
- There is a need to capture the expected value impact over time and product population, incorporating uncertainty in the results.

Ultimately, decisions in a for-profit firm have to be made on the basis of financial considerations. Therefore, we believe that incremental net present value (ΔNPV) is the most useful metric for technology decision making. The revised Technology Infusion Analysis (TIA) framework is shown in Figure 5. This is a modified version of Figure 3, the original technology infusion analysis framework. One of the biggest changes is that "risk" and "opportunity" are replaced by the expected marginal net present value (E[ΔNPV]) and standard deviation of the expected marginal net present value (σ[ΔNPV]).

The process consists of 10 steps as shown in Figure 5. Some of these steps have to be carried out sequentially, while others can be executed in parallel.

4.2. Step 1: Construct Baseline System DSM

As the first step, a Design Structure Matrix (DSM) [Eppinger et al., 1994] needs to be created to generate a matrix representation of the baseline product / system. In this study, a DSM technique developed by Smaling and de Weck [2007] is used, which can represent physical connections, as well as mass flows, power flows, and information flows, all in one matrix. An example system (DSM) shows the main elements or sub-systems as the rows and columns of a matrix. The connections between the elements are shown as the off-diagonal elements. Figure 6 shows how to read a highly simplified DSM matrix for a simple system composed of three components A, B, and C.

In this example component A physically connects to B which in turn is connected to C. A mass flow occurs from B to C, while energy is supplied from A to B and C, respectively. Additionally, A and B exchange information with each other.

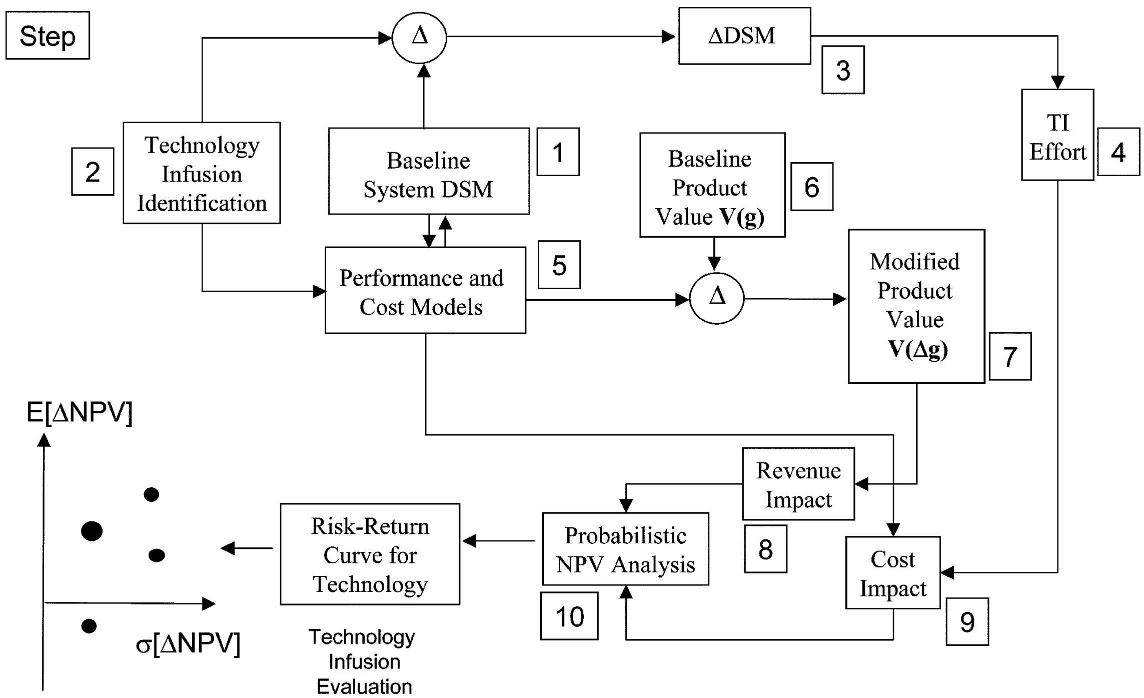

Figure 5. Nominal proposed Technology Infusion Analysis framework (TIA).

Such a DSM forms the basic information upon which the subsequent analysis builds.

4.3. Step 2: Technology Infusion Identification

In step 2, a candidate technology is identified, along with different ways or concepts in which the technology could be infused. If there are several competing technologies, one must select the set of technologies with the best potential. In the work by Smaling and de Weck [2007], a fuzzy Pareto-frontier analysis was used to select top concepts for a given technology.

4.4. Step 3: Construct ΔDSM

The next step consists of constructing a ΔDSM for a given technology infusion project. The purpose of this step is to capture all anticipated (or actual) changes that were necessary to accommodate the technology infusion. This is done by taking the baseline DSM structure (rows and columns) created in Step 2, keeping it as a reference, and clearing all entries and repopulating the matrix with only the changes that are necessary.

The substeps in step 3 are as follows:

- Capture all changes made to basic product/system to infuse the new technology.

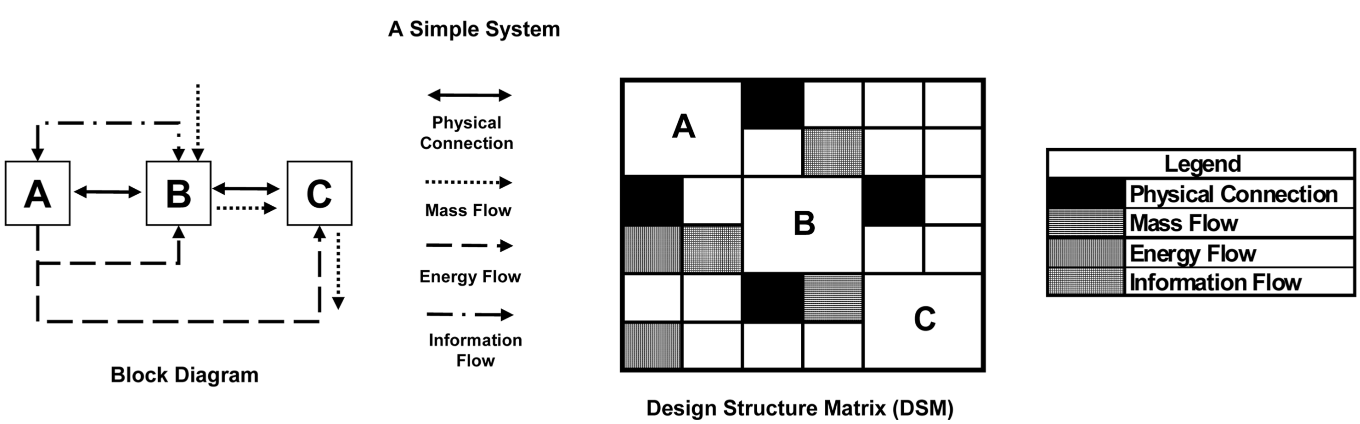

Figure 6. Block diagram (left) and DSM (right) of a simple system.

- Count the number of cells in the baseline DSM affected by the technology and list all the necessary changes in a change table.
- Compute the un-weighted technology invasiveness index (between 0 and 100%) using Eq. (1) in section 4.5.
- Separately estimate the nonrecurring effort (engineering hours) required to infuse the technology.

The ΔDSM uses a similar nomenclature as the baseline DSM. Additionally, new, modified and eliminated components are highlighted on the diagonal with pattern codes. Figure 7 shows an example of a ΔDSM for hydrogen fuel reformer technology infusion into an internal combustion engine from the previous case study [Smaling and de Weck, 2007], with appropriate pattern codes and explanation.

4.5. Step 4: Calculate Technology Infusion Effort

With the ΔDSM completed, one can calculate the *Technology Infusion Effort* (TIE), using Eq. (1) [Suh et al. 2008]:

$$TIE = \frac{NEC_{\Delta DSM}}{NEC_{DSM}} = \frac{\sum_{i=1}^{N2}\sum_{j=1}^{N2} \Delta DSM_{ij}}{\sum_{i=1}^{N1}\sum_{j=1}^{N1} DSM_{ij}}, \tag{1}$$

where

$NEC_{\Delta DSM}$ = number of nonempty cells in the ΔDSM,
NEC_{DSM} = number of nonempty cells in the DSM representing the original baseline product or system,
$N1$ = number of elements in the DSM,
$N2$ = number of elements in the ΔDSM.

$N1$ and $N2$ are allowed to be different in Eq. (1) because in some technologies new components have to be added, which will expand the scope of the underlying baseline DSM. However, since we are focusing on evolutionary improvements, $(N2 - N1)/N1$ will generally be less than 0.1.

TIE represents the relative system change magnitude, with respect to the complexity of the original system due to technology infusion. One also needs to estimate the amount of resources and effort needed to make each individual design change and also estimate the effort associated with system integration. Two changes may contribute equally to TIE, but may require vastly different amounts of resources to implement. Usually, experts from relevant fields are consulted to estimate the amount of engineering effort and investment required to accommodate changes specified in the ΔDSM. This is then translated into monetary value. This is considered as nonrecurring engineering cost, which is an upfront irreversible investment for infusing the technology into the product.

4.6. Step 5: Performance and Cost Models

Step 5 includes the construction or adaptation of models that allow simulating the system's performance, reliability and operating cost with and without the new technology. The

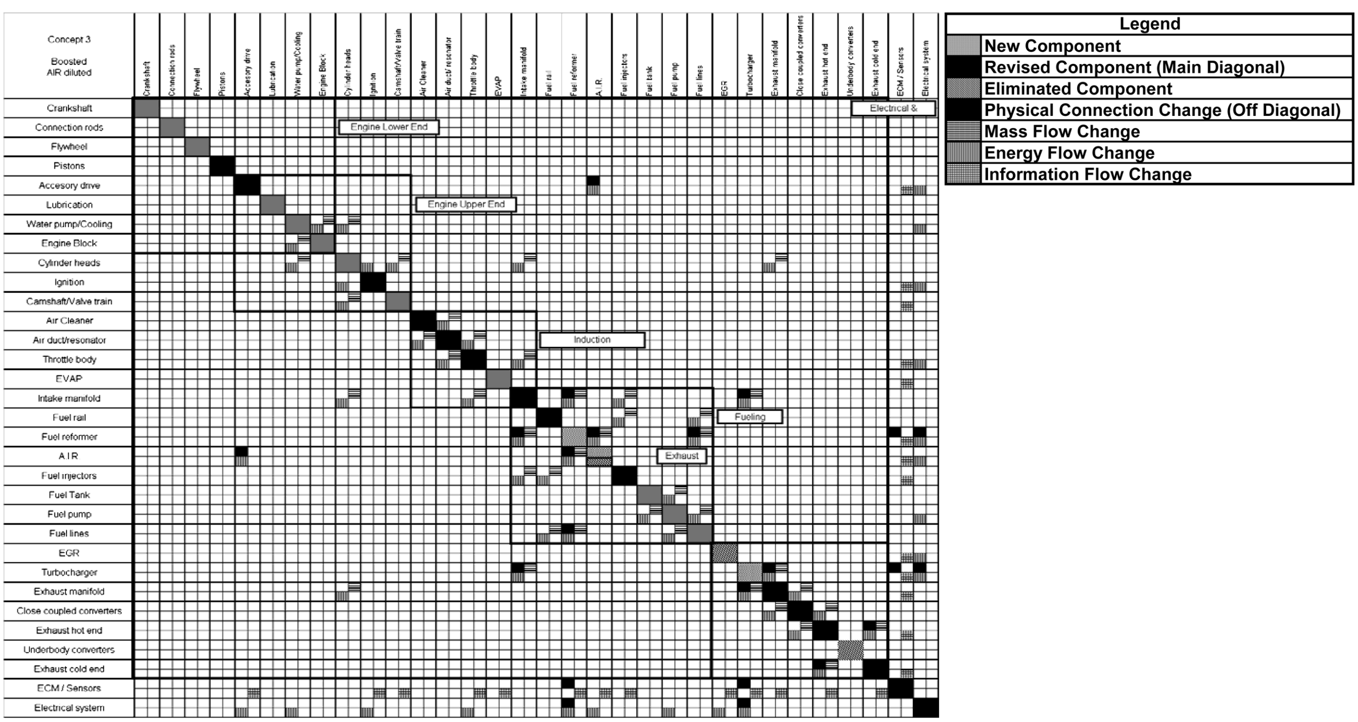

Figure 7. An example ΔDSM for fuel reformer technology infusion and ΔDSM pattern codes.

sophistication of this estimation can vary widely depending on how well a particular technology has been characterized. This step typically also includes an estimation of the technology impact on add-on unit cost.

4.7. Step 6: Estimate Baseline Product Value V(*g*)

Next, in step 6, we generate an estimate of the value $V(g)$ of the baseline product. For an existing product or platform this can be inferred from market data. For a new product it has to be estimated from the bottom-up using product functional characteristics g. We use Cook's product value methodology [Cook, 1997] to estimate product value.

According to Cook, value has the same units as price, is larger than the price if there is demand for the product, and is proportional to demand. Using the S-Model based on market equilibrium, the aggregate value of the ith product can be calculated using

$$V_i = \frac{N[D_i + D_T]}{K[N+1]} + P_i, \tag{2}$$

where

V_i = value of ith product,
N = number of competitors in the market segment,
D_i = demand for ith product,
D_T = total demand for the market segment,
K = market average price elasticity (unit/\$),
P_i = price of ith product.

Also, the value of the product can be calculated "bottom-up," if data for relevant product attributes are known. The value of the ith product can be expressed as the value function of product attribute $v(g_i)$, as shown in Cook [1997: Chap. 5]:

$$V(g_1, g_2, g_3, \ldots, g_j) = V_o v(g_1) v(g_2) v(g_3) \ldots\ v(g_j), \tag{3}$$

where

V = value of the product with j attributes,
V_o = average product value for the market segment,
$v(g)$ = normalized value for attribute g.

The value of individual product attribute $v(g_j)$ is derived from Taguchi's cost of inferior quality (CIQ) function, where certain product attribute values can be expressed as smaller is better (SIB), nominal is best (NIB), or larger is better (LIB) functions. Normalized value for a single attribute g can be calculated using

$$v(g) = \left[\frac{(g_C - g_I)^2 - (g - g_I)^2}{(g_C - g_I)^2 - (g_o - g_I)^2}\right]^{\gamma}, \tag{4}$$

where

g_C = critical value for the attribute, where if the product attribute value exceeds or falls below this value, the value of the attribute goes to zero, making the product undesirable,
g_I = ideal value for the attribute beyond which no additional gain in value can be achieved,
g_o = market segment average value for the attribute,
γ = value which controls the slope and shape of the value curve.

The baseline product value can be calculated using a combination of Eqs. (2)–(4).

4.8. Step 7: Calculate the Value of the Product with the New Technology Infused

Step 7 quantifies the modified product value $V(\Delta g)$ assuming that the new technology has been successfully infused. This assumes that the impact of the new technology will be "incremental" in the sense that the functional attributes remain between their critical and ideal bounds. As explained in Cook's work, product attributes always fall into one of the following three categories: (a) smaller-is-better (SIB), (b) larger-is-better (LIB), or (c) nominal-is-best (NIB).

4.9. Step 8 & 9: Estimate the Revenue and Cost Impact

In step 8, knowing the modified product value, the products offered by competitors as well as an assumed price policy, we can estimate the revenue impact that a new technology may have based on changes to market share and the anticipated number of units sold per time period. In step 9, the impact on cost is estimated by taking into account product run cost and manufacturing cost (from step 5) as well as nonrecurring effort for technology infusion (from step 4).

4.10. Step 10: Probabilistic NPV Analysis

In step 10, a probabilistic simulation is performed, for example, using Monte Carlo simulation, to estimate the distribution of NPV outcomes that may result in the future. This accounts for various uncertainties such as the technology infusion effort itself, the performance of the new technology as well as how the market may respond to the new technology. *At present we do not capture the potential impact of competitor behavior in this analysis*. The result is a distribution of ΔNPV for each technology concept. We care primarily about the expected value and dispersion of that distribution. Thus, each technology can be assessed in terms of $E[\Delta NPV]$ and $\sigma[\Delta NPV]$. This allows identifying promising technologies on a risk-return plot as shown in Figure 1.

4.11. Differences from Previous Work

There are some differences in how the TIA was developed and demonstrated, compared to the work done by Smaling [2005]:

- Many of the steps in Smaling's work focused additional effort on step 2. However, in the case study for TIA, more emphasis was placed at determining the total value of the alternatives versus techniques for the automated generation and filtering of various infusion concepts to be generated.

- In the TIA no weighting factors were used for different kinds of changes. This would be a topic for further refinement of the proposed process.
- Less focus in this version of the TIA is placed on the evaluation of technology under different scenarios, which was the case in the previous framework. In the case study presented later, there is only one scenario. However, with inputs from the business groups, different scenarios could be modeled to evaluate the impact of the technology.
- Scenarios could force different overall demand functions based on where the competition moves on the value curves or differences in the gammas (γ)—expressing value curve sensitivity—associated with the value curves because what is important to the customer may change over time.

The theoretical background of the proposed technology infusion process has been presented in this section. In the next section, the proposed methodology is demonstrated through an industry case study, where a novel value-enhancing technology is infused into a complex digital printing system.

5. CASE STUDY: TECHNOLOGY INFUSION IN PRINTING SYSTEM

The printing industry is a fiercely competitive industry, where many companies vie for market share. Currently, the trend in this industry is that the total pages printed in black and white are declining, while the total pages printed in color are increasing rapidly. Additionally, digital printing systems are starting to compete with traditional offset printing systems by offering offsetlike prints at competitive prices with additional flexibility and short-run capabilities. In the range between in-home low-cost digital printers to large commercial offset printers, there are many products to choose from.

Companies compete to gain market share and profit by delivering increased customer value along several dimensions, such as price, printer productivity improvement, service cost reduction, workflow improvement, and image quality improvements.

In a production printing system (a system where the print produced is the actual product sold to the end customer), all of these attributes are important. As a result many innovative technologies are being developed which drive improvements in one or more of these attributes. One such technology is being considered for inclusion into a next generation printing system, which is being updated from the printing system generation currently being sold. While the details of the technology are abstracted here to preserve confidentiality, we can state that the technology serves to both enhance the output quality of the printing system and reduce its operating costs.

The technology infusion methodology was used to evaluate the magnitude of change propagation, cost, and benefits for this particular technology. The name of the product, cost data, and associated technology were disguised and normalized in this paper.

5.1. Step 1: Construct Baseline System DSM

The first step is to characterize the current product by constructing the DSM representation of the system. This type of component-DSM maps the connections between components or subsystems of the product.

Before this can be done the system needs to be decomposed into components and/or subsystems. The level of granularity (abstraction) in the DSM is an important decision that depends on the complexity of the underlying product, the type and maturity of technology to be infused and the time available for technology assessment. If the DSM is very small (smaller than 15×15, for example) not much information may be gained. If the DSM is very large (greater than 100×100, for example) the effort involved in creating the DSM manually may be overwhelming. In this case study, the entire system was decomposed into 84 elements.

It is important to recognize that the scope and granularity of the DSM that is created has an effect on the rest of the analysis using the DSM and the subsequent ΔDSM. Scope and granularity as it applies in this context are described as follows:

Scope: The breadth of subsystems, components, or elements of the system included in the DSM. The boundaries of systems are sometimes difficult to define. The choice of the system boundary used will drive the work to develop or update the DSM and the apparent magnitude of the changes identified.

Granularity: This is the level of detail described by the choices of the subsystems, components, or elements found in the DSM. The level must be appropriate for the kinds of anticipated changes but not be at such a fine level that the DSM modeling effort is the equivalent of a detailed design project. Determining the level of detail appropriate for the DSM also will drive the work and the change metrics as well.

Based on our experience we found that a good rule of thumb for the effort involved in building a DSM model of a complex electro-mechanical product is:

$$T_{DSM} = 0.02 \cdot N_e^2, \quad (5)$$

where

T_{DSM} = number of work hours required to build a DSM model,
N_e = number of elements in the DSM.

Thus, a 20×20 DSM will take approximately 8 work hours to build, while an 84×84 DSM will require close to a person month worth of effort (~140 hours). The available data sources upon which this rule of thumb was derived included (i) a product prototype in the laboratory for visual inspection, (ii) extensive service and repair manuals, and (iii) drawings and subsystem experts. Future work may be required to further validate this relationship.

A DSM optimized in scope and granularity to effectively evaluate the infusion of one technology may or may not be optimum when considering a different technology, for example one that impacts a different portion of the system. The tradeoffs between achieving a useful scope and granularity and creating a DSM of manageable size is a point requiring careful consideration.

In the DSM, four types of interconnections between components and/or subsystem are modeled: physical connections, mass flow connections, power flow connections, and information flow connections. A brief explanation of each connection, with an example of each connection's representation in the DSM, is presented below:

Physical Connection: Physical connections show how elements within the system are physically connected, either by welding, bolted joints, or other means. Figure 8 shows the physical connection representation of the printing system CPU. Note that the connected components are represented by black color filled cells in the matrix. Also, for the physical connection, cells are filled symmetrically with respect to diagonal cells because the connection is bidirectional. In this DSM, software which physically resides in circuit board #1 is represented as a physical entity, with a physical connection to circuit board #1.

Mass Flow Connection: In the printing system, there are many different types of mass flows throughout the system. Some of these mass flows are media (paper), toner particles, and controlled air flow. Figure 9 shows a paper path subsystem of the printing system, with paper and toner (on the paper) flow represented with horizontal line patterned cells. Since mass flows can either be one way or circulating flows, the mass flow portion of the DSM does not have to be symmetrical with respect to the diagonal. In the example in Figure 9, paper flow is clearly a one-way flow.

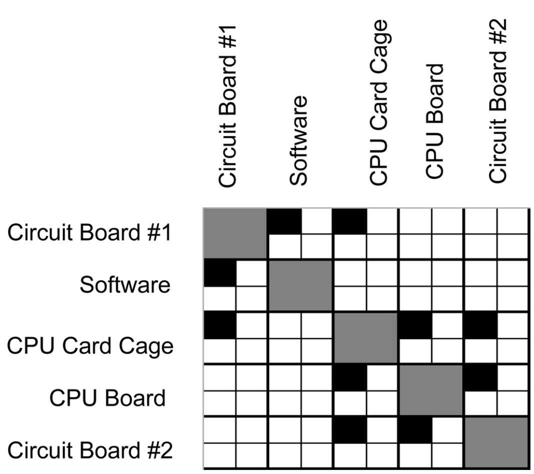

Figure 8. DSM representation of printing system CPU's physical connection.

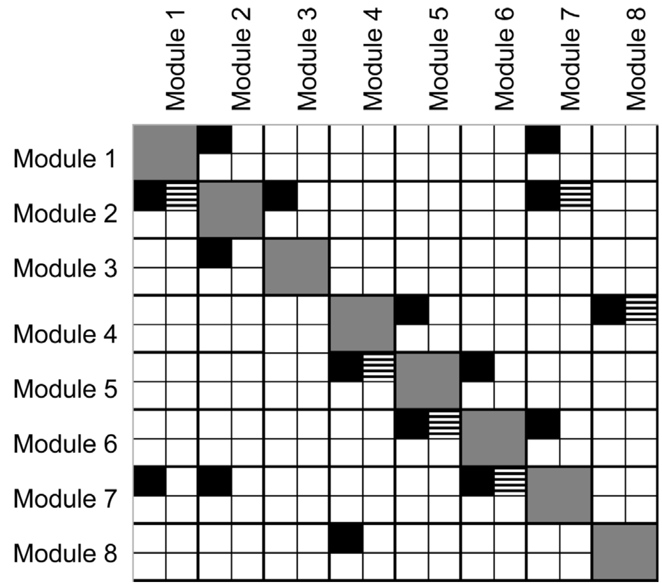

Figure 9. DSM representation of printing system paper path subsystem's mass flow.

Energy Flow Connection: Energy flow includes all flows related to power and energy transfer, including mechanical, heat and electrical energy. Figure 10 shows the mechanical energy flow within the printing system's paper path subsystem. Energy flow is shown here as vertical line patterned cells. Similar to the mass flow connection, energy flow can be one way or circulating.

Information Flow Connection: Information flow includes any information exchange between elements. Some of the examples are information exchanges between software modules and signals sent to servo ac-

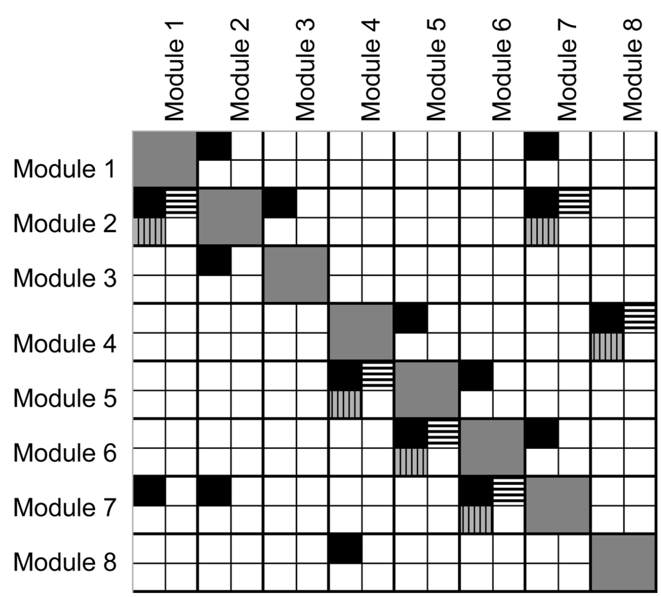

Figure 10. DSM representation of printing system paper path subsystem's energy flow.

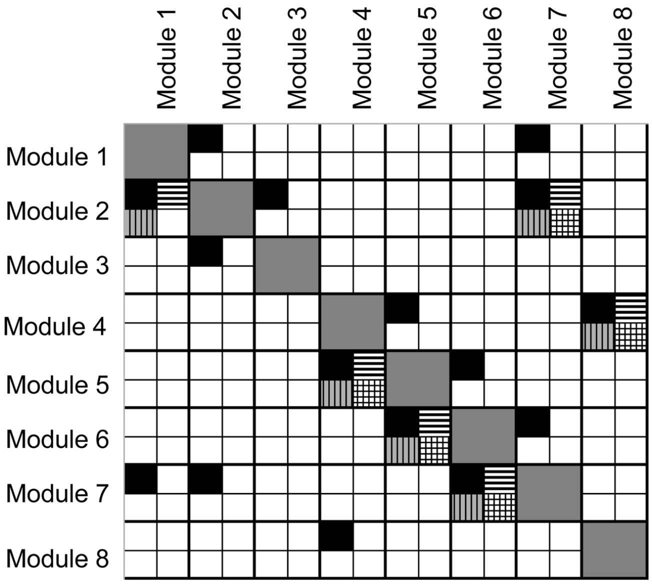

Figure 11. DSM representation of printing system paper path subsystem's information flow.

tuators for specific control action sequences. Figure 11 shows information flow of the paper path subsystem. The information flow is represented by grid patterned cells. In the figure, the information being carried through is the image information, which is represented by toner particles attached to the charged paper surface in the shape of the image.

Once all four flows are mapped to the DSM, the final baseline DSM representing the product is completed. The complete DSM for the baseline printing system is shown in Figure 17 in the Appendix. From inspection of the DSM, out of 27,972 possible connections, there are 1,033 nonempty connections for the entire system. This resulted in a Non-Zero Fraction (NZF) of 3.7%, where NZF is the ratio of nonempty connection to total number possible connections within the system [Holtta-Otto and de Weck, 2007]. It is interesting to compare the connection density of this product with that of other electro-mechanical products. An initial comparison with the NZF numbers reported in Holtta-Otto and de Weck [2007] for 15 different products and systems indicates that NZF = 0.037 is at the low (sparse) end of the range. Most products such as cellular phones, laptops, etc. yielded NZF values closer to the average density of 0.15. Note, however, that the reported NZF values may depend on the level of granularity in the DSM as discussed earlier. The largest DSM in Holtta-Otto and de Weck [2007] had $N = 54$ elements. A yet unproven hypothesis is that as the level of detail in a DSM increases (i.e., more elements N are represented in the DSM), the DSM (of the same system) tends to becomes sparser and the NZF values therefore drop.

5.2. Step 2: Technology Infusion Identification

Opportunities for product improvement are often identified through a combination of benchmarking, forward performance projections, customer feedback, and market research. These opportunities are then translated into needs and technical requirements through a number of techniques, such as the House of Quality [Hauser and Clausing, 1988]. In this case customer feedback and internal testing provided the needed assessment. Candidate technologies for inclusion in forward products are then proposed based on the identified need and the either hypothesized or demonstrated impact the technologies will have on that need. Other factors such as intellectual property, know how, and budget also play a role. In this case, a preliminary demonstration of technology capability showed that an approach was potentially viable and could address the defined need. The approach was then selected, but the details of how to best implement the technology and an assessment of the overall impact are the next steps. As addressed above, the technology considered in this case study is one that enhances the value of the next generation product by improving one of the following attributes: the variety of media that can be printed, print speed, reliability, run cost, and/or image quality.

5.3. Step 3: Construct A ΔDSM

In step 2 of the process, the need for technology infusion has been identified. Representation of concept infusion into the baseline product can be constructed in the form of a ΔDSM. A DSM has similar dimensions than the underlying DSM (i.e., $N2 \cong N1$) but captures only the engineering changes. The following steps were taken to construct the ΔDSM:

1 Empty all cells of the baseline DSM.
2. To the baseline DSM, add new rows and columns for $N2 - N1$ newly added elements and insert the names of the new elements.
3. For newly added, removed, or modified elements and connections, fill in the corresponding cells of the ΔDSM using the pattern coding scheme shown in Figure 12.
4. Note that both changes directly required by the new technology as well as indirect (propagated) changes should be included in the DSM [Eckert, Clarkson, and Zanker, 2004, Griffin et al., 2007].

Using the aforementioned guidelines, a ΔDSM for the newly infused technology was constructed. Figure 13 shows the completed ΔDSM for the new technology. In the figure, only those elements which are affected by the technology infusion are shown. Overall, there are 15 elements (compo-

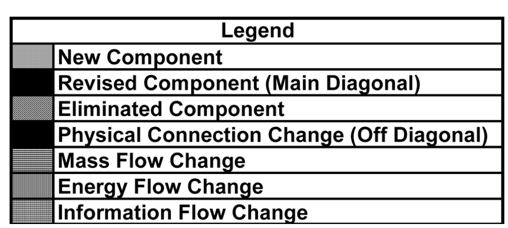

Figure 12. ΔDSM pattern codes (repeated from Fig. 7).

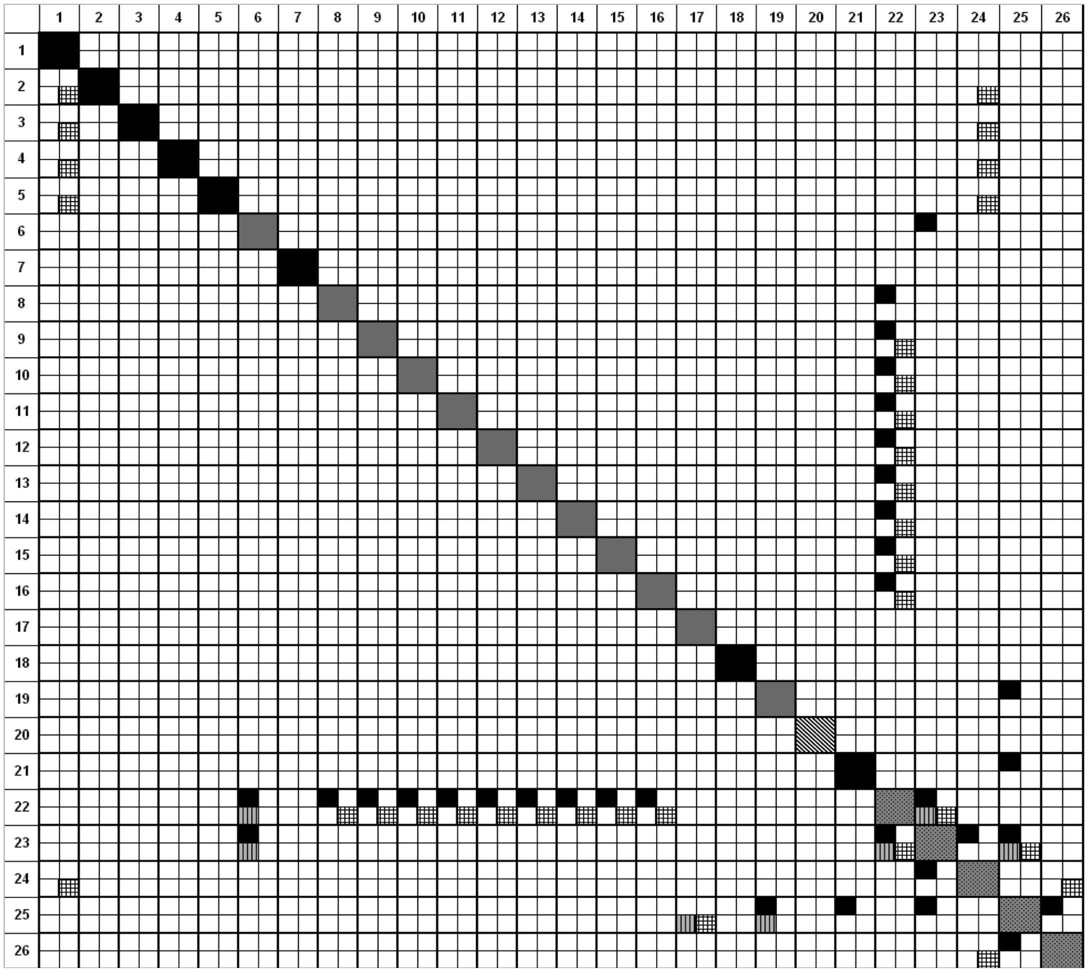

Figure 13. ΔDSM for newly infused technology.

nents) that were added/eliminated/revised, 33 physical connection changes, no mass flow changes, 7 energy flow changes, and 32 information flow changes for a total of 87 changes. The next step is to calculate the *TIE* using Eq. (1).

5.4. Step 4: Calculate Technology Infusion Effort

Using the number of connections and elements in the baseline DSM and in the ΔDSM, the *TIE* is calculated using Eq. (1). As it turns out, the infusion of technology resulted in 8.5% change to the original baseline system. It should be noted that the *TIE* is highly sensitive to the granularity of system decomposition. When comparing several different infusion concepts for a technology in terms of change magnitude, one must ensure that the original DSM and ΔDSM are properly decomposed, and able to show the level of technology infusion in a consistent manner.

With the results of the ΔDSM, the engineering team was consulted to estimate the total effort in terms of time and resources for technology infusion. The technology infusion effort falls into the following three categories:

- Component design/redesign effort
- Interface design/redesign effort
- System integration effort.

While component-level and interface effort can be directly obtained from the ΔDSM, system integration effort such as software configuration management, prototyping, and system-level functional testing is typically assessed as an overhead on top of the other two types of efforts. The technology infusion effort obtained in this way is used for the subsequent ΔNPV calculation.

5.5. Step 5: Performance and Cost Models

A number of established models were employed to estimate the performance improvements. These models were often at a high level (estimates of HW and SW complexity relative to other systems, estimates of development time, etc). In this case, with the introduction of a new technology into the system, a new performance model had to be developed that would predict the customer perceived output performance based on the engineering variables available to the engineering and technology teams. This model supplemented and was correlated to laboratory test results in order to make the necessary performance predictions with confidence.

Cost models that evaluated both the expected change in the unit manufacturing cost of the overall system and the expected change in the cost of producing prints with the printing system were developed primarily based on similar information collected for the existing printing system into which the new technology is being infused. The cost of producing prints is influenced by many factors, including (for example) the cost of materials to make prints and the cost of servicing the printing system.

5.6. Step 6: Estimate Baseline Product Value V(g)

Once the technical information for technology infusion has been gathered, one needs to estimate the current product value in the market segment it is competing in. The printing system for this case study competes in the digital production printing market segment with several other competitor products. Using the 2006 market segment data, the value of the baseline product V_i is calculated from Eq. (2). The value of K, the price elasticity, is adjusted so that the product value V_i is approximately twice the product price P_i, consistent with Cook's assumption for the automotive industry [Cook, 1997].

The product attribute curve for the selected performance metric is needed to estimate the value change of the product due to infusion of the technology. Equation (4) is used to construct the performance metric value curve. Critical, ideal, and nominal values for the performance metric were provided by the engineering team responsible for technology development.

5.7. Step 7: Calculate the Value of the Technology Infused Product

Using the attribute value curve created in step 6, and with the estimated improvement in the performance metric provided by the engineering team, the value of the technology-infused printing system is calculated. Figure 14 shows the performance metric value curve, indicating the current position of the product, and the expected position of the product when the technology is enabled.

Equation (3) is used to calculate the new value of the product with the new technology infused. Substituting the new value V_i into Eq. (2), a new demand D_i is obtained. This calculation assumes that competitors will continue to offer their existing products at the same value and price points in the future.

5.8. Step 8 & 9: Estimate the Revenue and Cost Impact

The new technology improves the customer relevant system performance, thus increasing the number of units sold (as calculated in step 7) and in this case also decreases the service cost to the company by further reductions in printing system downtime, labor, and parts. The following general assumptions are made for revenue and cost impact:

1. The new product will be produced for 5 years.
2. The service life of the product is 5 years.
3. Impact on the revenue is realized by service cost reduction per every 1,000 prints.
4. There is a nonrecurring investment cost for 3 years before the launch of the product due to new technology infusion.
5. There is added per unit cost for the technology installed in individual products.

Non-recurring investment cost, unit cost for the new technology module and service cost savings per 1,000 prints were provided by the engineering team. Using the gathered information, a nominal discounted cash flow chart (normalized) has been created, and is shown in Figure 15. This chart shows the incremental cash flows for the product due to the new technology, resulting in a marginal ΔNPV.

During the first 3 years, the technology is developed and integrated into the product, resulting in a negative delta cash flow relative to the estimates for the new product without the

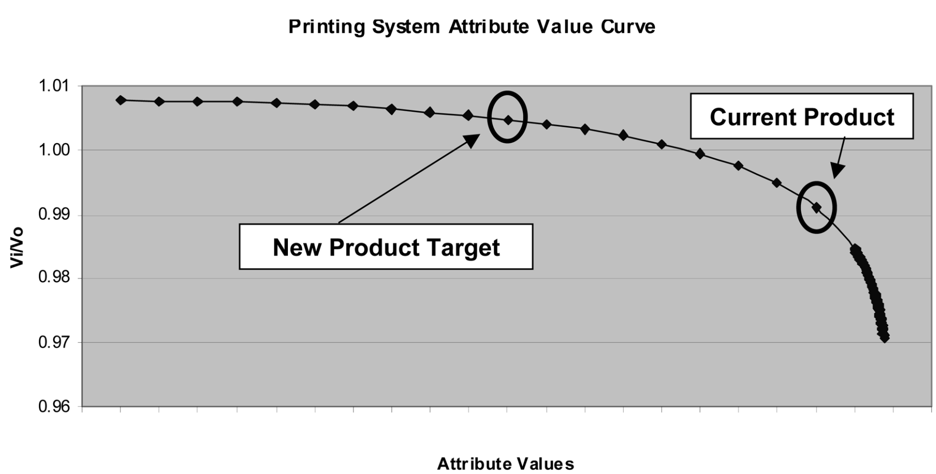

Figure 14. Value curve for customer relevant performance metric.

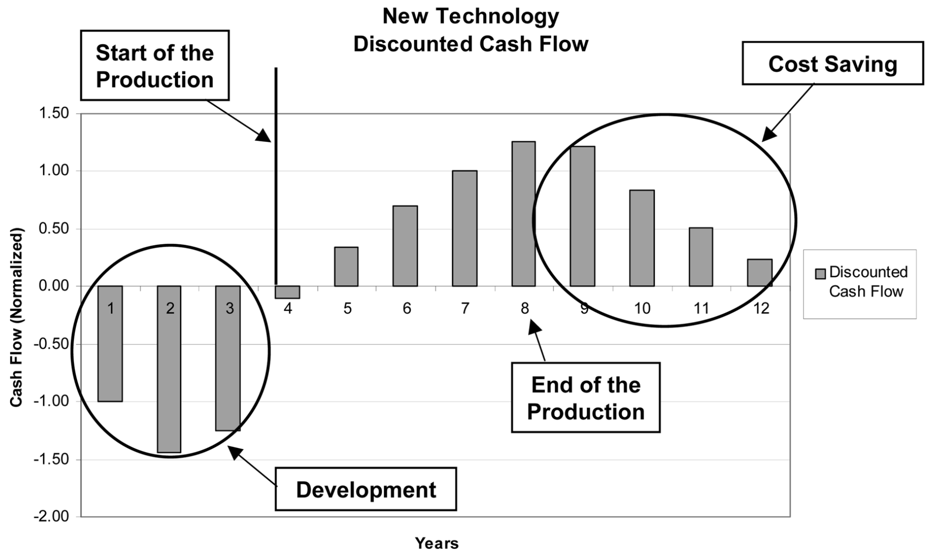

Figure 15. Nominal ΔNPV chart for new technology.

this particular new technology. The product launches in year 4, but the total cash flow remains negative, due to an initially small number of machines placed and prints produced in the field. The product is discontinued at the end of year 8, but technical support for fielded machines continues. From years 9–12, there is positive cash flow realized from the service cost savings of machines operating in the field. Cash flow gradually decreases from year 9 to 12 as machines placed in the field are being retired after having exhausted their assumed product life (5 years).

5.9. Step 10: Probabilistic NPV Analysis

A nominal ΔNPV is calculated in Step 8 & 9. However, since the future product demand and service cost savings are uncertain, probability distributions are assigned to each year's demand and average machine population cost savings for that year. Monte Carlo simulation was performed using the Crystal Ball® software. For the Monte Carlo analysis parameters, yearly demand for machines, and the service cost reduction per 1,000 prints were selected. As a result, Figure 16 shows the normalized range of total cash flow for the life of the technology.

In this case the overall range of cash flows is always positive, even under the most pessimistic scenario. If there are several competing concepts for technology infusion, one can calculate the ΔNPV for each concept to choose the one that gives the largest return on investment.

5.10. Case Study Summary

In this section, the technology infusion framework shown in Figure 5 was demonstrated through a printing system case study, where a value-enhancing technology is infused into an

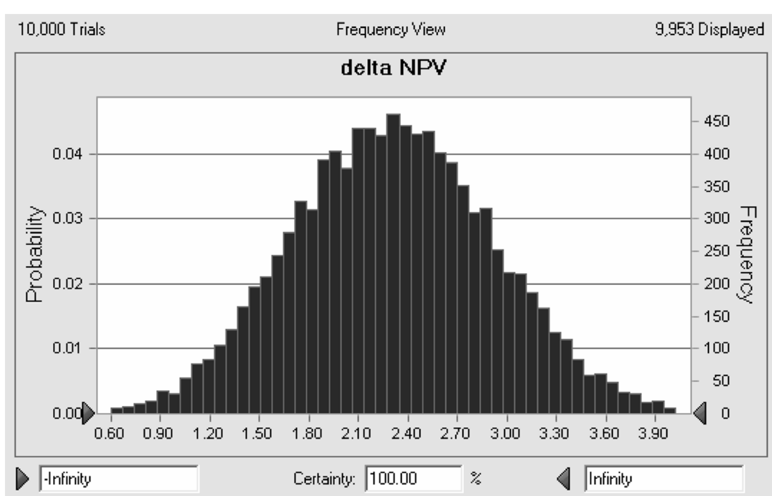

Figure 16. Range of ΔNPV for new technology infusion.

existing product to improve the performance of the system. A baseline product DSM of dimensions 84 × 84 and a technology ΔDSM were created to estimate the change propagation of the system and the actual effort required to make required changes. The DSM had a nonzero fraction of 3.7% and the ΔDSM suggests a technology invasiveness index of 8.5%. Performance improvement, revenue, and cost impact were estimated through expert engineering assessment and product attribute value curves. Finally, a range of possible financial outcomes was captured through Monte Carlo simulation, where uncertain critical parameters were varied within assigned probability distributions. It was demonstrated that this methodology can successfully be implemented with reasonably available data. The total effort to construct the baseline DSM model of the system was about 140 hours, while the entire technology infusion study took about 9 months to conduct.

6. CONCLUSION AND FUTURE WORK

In this paper, a new process for evaluating the impact of technology infusion is introduced and demonstrated through a printing system case study. The proposed framework utilizes DSM, ΔDSM, value curves, and ΔNPV analysis to estimate the overall cost and benefit of new technology infusion into a parent product. The methodology was demonstrated through a digital production printing system case study, where a new value enhancing technology was infused into an existing printing system, causing a technology invasiveness of 8.5%. It should be pointed out that the technology invasiveness index by itself is only an approximate indication of the level of change required by a technology. One could envision a DSM that contains only few changes, e.g. resulting in a small TIE of only ~1%; however, these few changes could be much more difficult to implement than another larger TIE on the order of ~10% containing many but relatively simple changes. This is why it is critical to not only compute the TIE, but to also translate the changes captured in the ΔDSM into actual anticipated change effort expressed as person-years of nonrecurring engineering effort.

The total part-time effort for conducting the study was 9 months of which one person-month was spent building the underlying DSM model. The relationship $0.02N^2$ can be used to estimate the number of work hours required to build a DSM model of the system. The study showed that, despite the required nonrecurring engineering effort to infuse the technology, a positive marginal net present value would result over a 12-year time horizon.

There are several directions for future work. One avenue is to investigate the impact on the system when a *set* of technologies is infused together. In reality, when a complex product like a digital printing system is upgraded from one generation to the next, several new technologies are implemented into the system at once. Investigating the technology interaction—both in the design space and in the performance space—would be a very interesting and relevant topic. Another topic of interest is the establishment of DSM and ΔDSM construction and complexity management guidelines for consistent and repeatable execution. The concept of hierarchical DSMs may be helpful in achieving both model fidelity and reasonable modeling effort. More research needs to be done to investigate the proper level of system decomposition, given a set of technologies or several different concepts for comparison. In terms of estimating technology infusion effort (step 4) we found that component-level changes and interface changes can be directly read from the DSM but that accurate estimation of the system integration effort requires more research. Recent research on estimating and optimizing system integration processes [Tahan and Ben-Asher, 2008] may be helpful in this respect. Another future work which can enhance this methodology is quantifying the potential impact of competitor behavior and implementing this in our cost-benefit analysis. Also, product attribute value curves for specific industry or market segments can be further refined to more accurately reflect the anticipated response of future customers. Finally, this research framework can be extended (with some modifications in risk-benefit analysis) to nonprofit sectors, such as government agencies, where the mission utility is a driving concern.

7. NOMENCLATURE

DSM Design Structure Matrix
GUI Graphical User Interface
NPV Net Present Value
NZF Non-Zero Fraction
RVI Relative Value Index
$E[\Delta NPV]$ Expected Marginal Net Present Value
$\sigma[\Delta NPV]$ Standard Deviation of the Expected Marginal Net Present Value
D_T, D_i Total demand for the market segment and demand for ith product
g_C Critical value for the attribute
g_I Ideal value for the attribute
g_o Market segment average value for the attribute
K Market average price elasticity (units/$)
N Number of competitors in the market segment
N_e Number of elements in the DSM
$NEC_{\Delta DSM}$ Number of nonempty cells in the ΔDSM
NEC_{DSM} Number of nonempty cells in the DSM
$N1$ Number of elements in the DSM
$N2$ Number of elements in the ΔDSM
P_i Price of the ith product.
T_{DSM} Number of hours required to build a DSM model
V Value of the product
V_i Value of the ith product
V_o Average product value for the market segment
$v(g)$ Normalized value for attribute g.

APPENDIX: DSM OF THE BASELINE PRINTING SYSTEM

Figure 17 shows the complete DSM representation of the baseline printing system. The DSM consists of 84 elements, and shows physical connections (black cells), mass flows (horizontal line patterned cells), energy flows (vertical line patterned cells), and information flows (grid patterned cells) within the system.

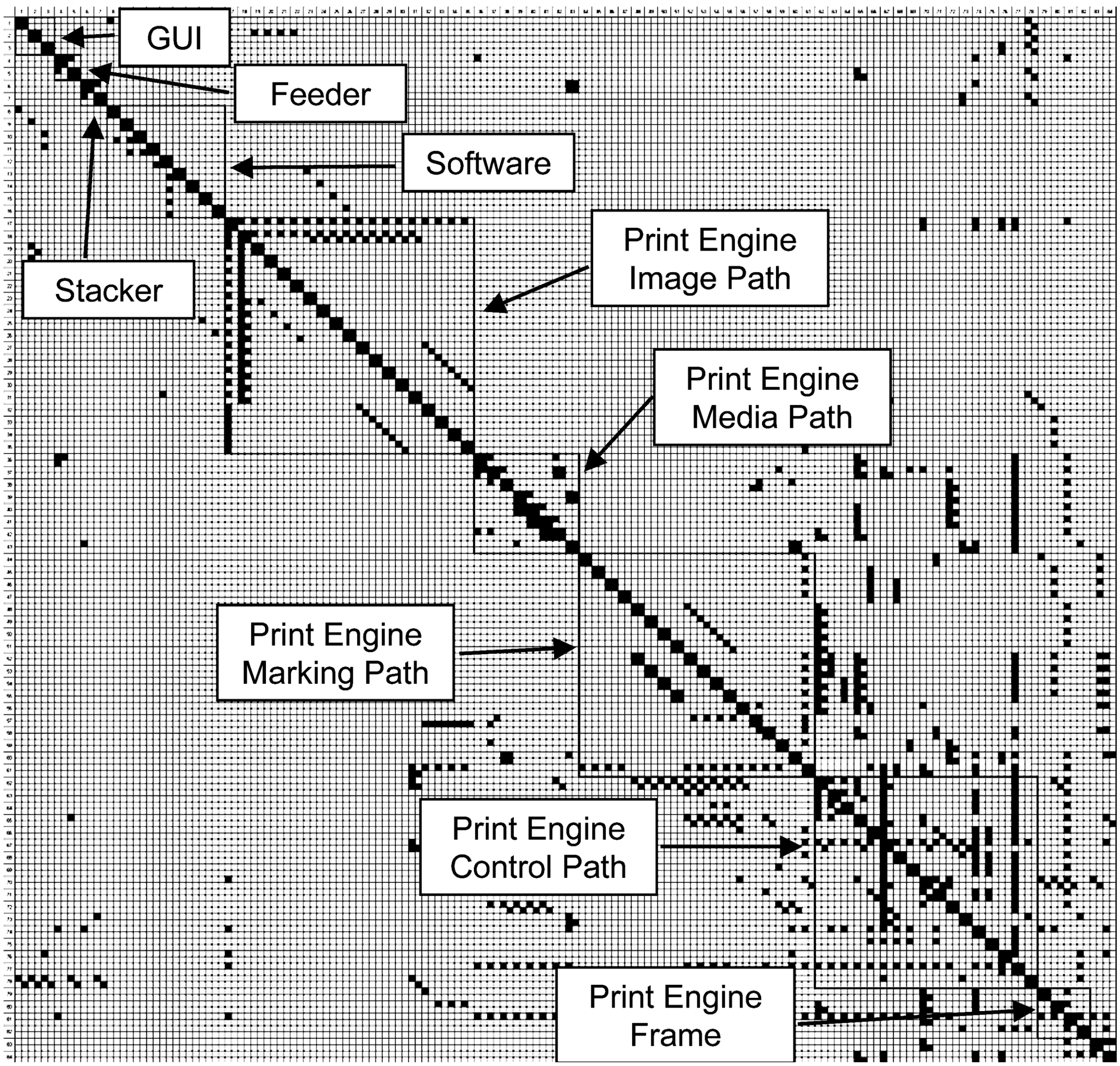

Figure 17. Baseline DSM of the current printing system product.

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