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EXPLORATION OF THE USE OF DESIGN METHODS WITH THE DESIGN STRUCTURE MATRIX FOR INTEGRATING NEW TECHNOLOGIES INTO LARGE COMPLEX SYSTEMS

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ABSTRACT

Integrating products of basic technology research and development efforts into Large Complex Systems (LCSs) requires systematic approaches. It has been observed that because of the complexity associated with LCSs, no single structured design method will suffice for integrating new technologies into an LCS. In this work, we explore through the literature how an integrated design approach involving the Design Structure Matrix (DSM) with several design methods (mainly those involving other matrix-based methods) might support the introduction of new technologies into large complex facilities. The survey presented in the paper could provide support for future investigations on how to align the outcomes of R&D processes with the requirements of introducing technologies in target LCS. Also it could help in developing future understandings about transitioning basic outcomes of R&D into technology products and services.

Keywords: Large Complex Systems, Design Structure Matrix, New Technology Infusion,

INTRODUCTION

Newly developed technologies only deliver value when deployed and integrated successfully into existing systems. Integrating new technologies into existing Large Complex Systems (LCSs) can be quite difficult [1]. There are growing needs for developing methodologies and tools that systematically support integrating new technologies in LCSs and redesigning the LCSs accordingly. Current analysis approaches for LCSs lack coherent frameworks for assessing technology infusion and concept selection. The literature on technology readiness is quite abundant; however there is a lack of rigorous approaches for assessing benefits, costs and risks of infusing new technologies in existing system designs [2]. The current tools provide means for assessing maturity of technologies between the conceptual, development and operational phases. However, the available tools for assessing technology maturity do not assess difficulty levels for transitioning technologies from laboratory environments to operations in existing systems. The ability to undertake and manage changes that result from any new technology infusion in an existing LCS is related greatly to understanding the links that exist between different components (or subsystems) of the system and the impact they will have on the propagation of any change in the system. This is why it is important to identify what changes are required for infusion of a newly developed technology in existing LCSs. The earlier these changes are predicted during the design process for the new technology, the less expensive it becomes to undertake the development of the technology and the easier it becomes to insert the technology in an LCS.

Developing new technologies for clean water production, a strategic need for Saudi Arabia, is the objective of a joint MIT-KFUPM research program involving some 30 faculty from the two universities. Part of the joint research team is working on developing a frame that enables the researchers not only to monitor continuously the advancement and level readiness of the underdevelopment technologies, but as well to develop strategies for technology infusion in existing LCSs. This includes identifying design and product development tools that could help in transitioning R&D results into technology products and services.

Integrating products of basic technology research and development efforts into LCSs requires systematic approaches. Combining the Design Structure Matrix (DSM) with several other design methods was identified as a potential technology deployment approach. This work explores through a review of the literature ways that an integrated design approach involving the DSM with several design methods might support the introduction of new technologies into large complex facilities such as the clean water generation facilities relevant to the MIT-KFUPM research program through alignment of the research efforts with the requirements of the target LCSs. Product designers, developers and engineers recognize the DSM strengths for managing different aspects of the product development processes. It is widely agreed that the DSMs can be used for modeling LCSs and useful in understanding and improving complex manufacturing and technology development processes. Several design approaches combine the DSM with other design tools and methods for handling the challenges of managing LCSs. This feature enables the DSM to support analysis of insertion of new technologies into LCSs as it has been observed that because of the complexity associated with LCSs, no single structured design method will suffice for integrating new technologies into an LCS.

In this paper, we explore the potential of using the DSM in an integrated manner with other design tools and system engineering methods. The purpose of this is to develop understandings about how to transition R&D results into technologies that could be deployed into LCSs. A review about the use of the DSM in technology infusion applications is presented. Also, a structured literature review about the integrated uses of DSM with other tools is discussed for reflecting how these can be useful in managing several aspects of new technologies integration in existing LCSs. It is anticipated the understandings developed from this work will help the MIT-KFUPM research teams in developing approaches that help in progressing the outcomes of their R&D activities.

DSM TECHNOLOGY INFUSION APPLICATIONS

The literature has documented a variety of situations in which a DSM matrix method is used to facilitate the deployment of a new technology. A methodology has been developed using the DSM to evaluate the impact of different product architectures during the conceptualization phase of a micro-turbine for electric power generation in several contexts and widely for cogeneration purposes [3]. The method depends on modeling a functional net during product conception by means of a graph structure and produces a set of solutions, each one characterized by a specific architecture or peculiarity. Each functional net version is then translated into a DSM for managing its complexity and, afterwards, to aid a reasoning towards the most sustainable solution. The procedure exploits the DSM for allowing product developers to collect data from links present in existing functional network and to show interactions exchanged in whole products and between the product and its environment. A technique was developed using the DSM for supporting design integration and reducing complexity of large-scale complex products [4]. The method enables redesigning complex products following technology evolution and was illustrated on automated guided vehicle systems. It can be used for finding solutions corresponding to customer requirements and constraints at an early stage of the redesign process, which facilitates new technology infusion in large-scale complex products. The technique includes an Integration DSM (I-DSM), which connects together the views through the main properties of the product; spatial, energy, information and material viewpoints; and it helps the designer both analyze the current solution and guide it towards new solutions following the technology evolution.

A DSM model was developed to estimate the technology cost against technology improvement [5]. The method depends on examining DSMs of different technologies, computing their complexities and comparing their rates of technology improvement. The methodology shows that DSM is useful in understanding and improving of technology improvement in complex manufacturing and technology development processes. DSMs were used for representing the architectures of existing turbofan engines and new-generation geared turbofans for comparing quantitatively the increase in architectural complexity against the predicted increase in engine performance [6]. The approach linked the architecture as represented by the DSM and functional groups by assessing the potential impact of the architecture on the organization and the integration effort. From the business impact perspective, using the analysis performed could provide some insight into the connections between architectural complexity and integration cost.

A new decomposition method utilizing the DSM and Axiomatic Design (AD) for defining design modules for emerging systems during the early design stage was developed [7]. The proposed decomposition method was applied to an HVAC system and the defined modules were analyzed. From the AD matrix obtained during the process, the design procedure of the system and the design processes of the modules were defined to design the system efficiently. In a paper that presents a technology infusion assessment methodology, the DSM has been used to quantify the potential performance benefits of new technologies using multi-objective Pareto analysis [2]. The methodology has been developed for primarily helping in dealing with intermediate steps in technology development and infusion, where the architecture of the parent system remains largely intact, but major subsystems are affected by infusion of a new technology. The methodology depends on defining types and numbers of changes required to infuse each technology concepts into the baseline system in the physical domain which is quantified with a component-based change DSM or simply ΔDSM. This ΔDSM captures the number of new components, components removed, components redesigned, new interconnections as well as changes in mass flows, energy flows, or signal/data flows required. These changes are identified with the ΔDSM for each concept and are then summarized using a Technology Invasiveness Index (TII) which acts as a surrogate for the amount of redesign cost and effort, but also for the internal uncertainty of actually achieving the technology benefits as predicted by the simulation. The larger the TII, the larger the uncertainty will be. This technology infusion methodology was demonstrated for a hydrogen-enhanced combustion engine, where the effects of integrating a plasma fuel reformer were quantified and discussed in terms of fuel economy, NOx emissions, and add-on vehicle costs. The DSM and ΔDSM were also used with a net present value analysis to calculate a Technology Invasiveness Effort index (TIE) to estimate the overall cost and benefit of new technology infusion into a parent product [8]. 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%. The methodology quantitatively estimates the impact of technology infusion through the use of a DSM and the creation of a 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.

The DSM was used for analyzing the change behavior in rotorcraft design of helicopters [9]. For this, DSM models were developed to predict the risk of change propagation in terms of likelihood and impact of change. A model linking the DSM with AD was used for upgrading a BAE SYSTEMS air defense system [10]. The study results indicated suitability of the model for updating existing systems rather than developing new systems.

INTEGRADTED USES OF DSM

Complexities of systems arise from their numerous elements and the multitude of inter-twined relationships between the elements. Analysis of deployment of new technologies into existing LCSs requires developing understandings about the hierarchies of these systems and the interdependencies that exist between their main components. This requires systematically breaking or decomposing the LCSs into sets of smaller systems (or subsystems). In doing so, product development and innovation processes can be accelerated and this allows subsequently for re-integrating the system components in a proper way after augmenting the new technology into the system [11]. Also, redesigning LCSs to accommodate new technologies requires efficient methodologies for predicting the changes that may happen to their parts as in most cases a change to one part of an LCS results in changes to other parts. Managing challenges of redesigning LCSs where different change propagation paths may be possible can be significantly enhanced by prediction of such changes. The knowledge of change propagation paths and their impact on existing LCSs allows directing the infusion of new technologies towards avoiding risky changes of the sub-systems and, where possible, allowing changes where they are easier to execute. Predicting the changes due to technology infusion enables the designers to capture the number of new components, components removed, components redesigned, new interconnections (and also the physical changes). Additionally, predicting the changes allows quantifying the risks and opportunities of new technology insertion into existing LCSs by evaluating the utility of future benefits and costs [9 & 2]. The following subsections discuss uses of the DSM with three tools namely; the AD, the Change Propagation Method (CPM) and the Quality Function Deployment (QFD). The integrated uses of these methods with the DSM are believed to significantly enhance the DSM capabilities to manage several aspects and challenges of technology infusion in LCSs.

Use of DSM with Axiomatic Design

The ability of DSMs to model interactions of components of complex systems and the Design Matrix (DM) of Axiomatic Design (AD) to relate the functional requirements to the physical components of a system, make the DSM and AD complementary tools for decomposing the LCSs and reintegrating them after infusing the new technologies. In the process of designing a complex system, it is necessary to structure the information and different parameters extracted at the decomposition phase, as well as to describe and plan the sequence of applications and interactions [12].

The complementarities between the AD matrices and the DSMs were demonstrated through the matrix transformation techniques that were developed for utilizing the AD-DSM arrangements for predicting the interactions of systems during the modular or incremental innovation stages (when the technology infusion processes usually take place) [13]. The paper shows that in incremental innovation, when both the core technology and the system interfaces do not change, the existing expert knowledge on the system and the components can be reused and a DSM can be built at an early phase of the technology infusion project, without having to construct a DM first. Then, if the engineers are interested in knowing how requirements relate to the system interactions, they may transfer the DSM into a DM for that purpose. On the other hand, in modular innovation, where the core concept of the module is usually changed and the system interfaces between the module and the rest of the system are not changed, the DSM for modules cannot be built from experts' past experiences, and must be built from the DM.

The joint ability of AD and DSMs to manage the modularization stage of existing systems was demonstrated by a process that was developed for decomposing-integration of complex product environments [7]. In this process, the Independence Axiom of AD and the DSM are utilized for efficient modularization of a design system and the design flow without feedbacks. In this method, the decomposition defines rational modules considering relationships between elements, and between functional requirements of the system and elements. For defining the rational modules, the AD and DSM are linked through the implicitly existing functional requirements in the DSM. The method was applied to a mount type HVAC system and the defined modules were analyzed. From the AD matrix obtained during the process, the design procedure of the system and the design processes of the modules were defined to design the system efficiently based on AD. The ability of the combined use of AD and DSM to modify existing systems for satisfying new system requirements was also demonstrated through function-based modular designs [14]. Through this approach, it was shown that the DSM and AD can be developed for modeling the decomposition and integration processes so as to capture complex system interactions, and to suggest task sequences to minimize rework. This enables the combination of AD and DSM to improve product innovation and development capacity, reduce the overall time and cost, and increase the competitiveness of their products and therefore this facilitates transitioning the technology from one stage into another one for an existing LCS.

The transposability between the two types of matrices (AD & DSM) was also shown to facilitate the decomposition and integration processes of new technologies in complex systems at earlier architectural innovation stages (prior to the modular and incremental innovation stages). This was demonstrated by a novel design decomposition model for complex product development environments, which combines the DSM and the AD to accommodate the iterative nature of the decomposition integration process of complex systems [10]. Similarly, a technique for obtaining a DSM from an AD matrix was developed to help engineers in a company to transfer the Electronic Chuck technology to a product design group so that the chuck can be integrated with existing wafer processing modules the company already had on the market [15]. The purpose of this case study was to construct a DSM prior to the occurrence of the design integration, in order to use the resulting DSM to guide the system integration and testing phase. The DSM and AD matrices were also used for developing an engineering requirements management method that assists product design engineers to know that the engineering requirements that need to be are rechecked when a design change is made [16]. This method has potential applications in complex systems such as automotive product development where there is a need always to represent the complex and inter-related design constraints of a mechanical design system. The method was applied successfully to capture the interrelationships of both the customer and engineering requirements for an automotive A-pillar design.

Use of DSM with QFD

The QFD is most commonly used in early phases of design processes for identifying the needs for product development for later deployment in downstream product development processes. On the other hand, the DSM provides the representation of the complex systems and provides the efficient support for product development and project scheduling. While the DSM lacks the upward linkage to goals, projects, and the needs for product development, the QFD does not address the essences of project management and processes of deployment. For deploying customer driven product definition to product design, a novel framework was developed for linking QFD to DSM [17]. This includes taking the requested parts characteristics from QFD to develop product architecture/ components and design activities, and then evaluate for design scheduling and costing. The developed framework was implemented in the semiconductor industry (system-on-a-chip (SoC)) for product design planning and development. The DSM was also used as an analysis tool for effective grouping of components of Green design and development of electronic products with the tasks for developing the products using QFD [18]. The complementary roles for DSM & QFD in developing complex product systems is due to their abilities to contain information spanning technological domains and to capture interrelations within classes of information and across product development domains [11]. The DSM and QFD are used jointly to enable implementing Concurrent Engineering (CE) in complex product development and innovation. They are used jointly to develop a CE overlapping model by first defining the complex product development project including contents, scope, and objective, etc., and then decomposing the complex product development project into some sub-activities [11]. The QFD was also found to be useful in enhancing other DSM capabilities for managing detailed information between the different elements of complex systems [11]. Utilizing the information contained in the QFD matrix and the information mapping and transferring across different domains for quantifying the dependency between design activities was found to be helpful in reducing the difficulties of constructing the numerical version of the DSM (NDSM) [19]. The NDSM could contain a multitude of attributes that provide more detailed information on the relationships between the different system elements and thus allowing for development of more complex and practical partitioning and tearing algorithms.

Use of DSM with Change Propagation Method (CPM)

The DSM has been used with another inter-domains matrix for modeling change propagation due to technological evolution in complex systems [1]. This matrix is derived using the Change Propagation Method (CPM) which has similarities with Axiomatic Design. The matrix-based model supported complex product development by simulating change propagation between product architecture and development organization. The method was applied to the development of a manual mechanical gearbox into a robotized gearbox. The change design structure matrices (ΔDSMs) were used for capturing the changes generated in the design of an emerging complex sensor system [20]. A DSM that represented the intended structure was created using the design documentation for a large data set containing thousands of change requests generated during the design of the complex system. Then, the data were analyzed to yield a ΔDSM, describing the actual change structure of the program. Although the DSM was used in this research as a tool for monitoring change propagations during the product development program, outcomes of the research reflect the DSM potential when employed with other CPM tools, to manage the risks related to rework caused by the changes. Although the DSM provides no direct indication as to the likelihood or scale of any such redesign, it may be used as the basis of a process simulation that includes consideration of rework [21], allowing the identification of critical process features that impact cost and schedule risk. Such an approach can be used, where the underlying process is known, to analyze the impact of planned design changes. This is how the DSM was employed for developing Compute Predictive Matrices that predict the change propagation in the flow of change from one sub-system to another, and the combination of changes from a number of sources to effect change within a particular sub-system [9]. The predictive model allows for both these behaviors and calculates a combined risk of propagation from its direct and indirect components.

CONCLUSIONS

In this work, we presented a review of literature that addresses practical applications for the DSM for technology infusion applications in complex systems. It is notably observed that the DSM uses for these applications were combined with other methods and tools, which is a common approach for handling the management of complex systems. Also, this work presented a structured review about the joint uses of DSM with other tools, namely the Axiomatic Design, the Quality Function Deployment and the Change Propagation Method. It was shown that the integrated processes of combining these methods with the DSM can facilitate deploying emerging technologies into existing LCSs. The survey on the joint DSM uses with other methods in technology infusion applications will help in laying the basis for future research investigations on developing methods for transitioning R&D results into technology products.

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