The University of Bradford Institutional Repository

Link to publisher's version: *http://dx.doi.org/10.1088/1757-899X/65/1/012005*

Citation: Uddin A, Campean IF and Khan MK (2014) Complex Product Architecture Analysis using an Integrated Approach. 27th International Conference on CADCAM, Robotics and Factories of the Future 2014. IOP Conf. Series: Materials Science and Engineering, Vol 65, Conference 1, pp 1-10.

Complex Product Architecture Analysis using an Integrated Approach

Amad Uddin[1, a], Ioan Felician Campean[1,b] and Mohammed Khurshid Khan[1, c]

[1] Bradford Engineering Quality Improvement Centre (BEQIC),
University of Bradford, United Kingdom, BD7 1DP.

[a]a.ud-din1@bradford.ac.uk, [b]f.campean@bradford.ac.uk, [c]m.k.khan@bradford.ac.uk,

Abstract. Product design decomposition and synthesis is a constant challenge with its continuously increasing complexity at each level of abstraction. Currently, design decomposition and synthesis analytical tasks are mostly accomplished via functional and structural methods. These methods are useful in different phases of design process for product definition and architecture but limited in a way that they tend to focus more on 'what' and less on 'how' and vice versa. This paper combines a functional representation tool known as System State Flow Diagram (a solution independent approach), a solution search tool referred as Morphology Table, and Design Structure Matrix (mainly a solution dependent tool). The proposed approach incorporates Multiple Domain Matrix (MDM) to integrate the knowledge of both solution independent and dependent analyses. The approach is illustrated with a case study of solar robot toy, followed by its limitations, future work and discussion.

1. Introduction

Complexity in product development is very common and emerges from many domains of design world. The product can be complex in its requirement, function, and form domains. Researchers often consider many other domains necessary and useful for the product design and architecture analysis [1]. Engineers tend to deal with product complexity by breaking down the complex problem into smaller problems [2, 3]. Many tools and methods are available to the engineers to manage, organize, and integrate the information of product complexity. There are two major aspects of product modelling in engineering design: *functional modelling* (also referred to as solution independent analysis) and *structural basis* (solution dependent analysis) [4].

In the *functional modelling*, the function of the product is decomposed into various sub-functions so that engineers can search solutions for each of the decomposed sub-function [3]. The function modelling technique has been discussed in many texts with various methods employment at the early stages in the design process. For example, Pahl et al. [5] describe structured methods to establish function structures in the conceptual design stage, where the product is modelled as a series of sub-functions via three distinct types of input and output: energy, material, and information; and thereafter to search for working principles and structures that fulfil sub-functions.

The product is also modelled through various methods by using *structural basis*. Among various methods, Design Structure Matrix (DSM) is readily available in literature and deals with the design of a product through decomposing and integrating it on structural basis and handling interactions or dependencies between the decomposed parts, mainly via qualitative and quantitative schemes. A comprehensive review of this method is provided by [6] and [7].

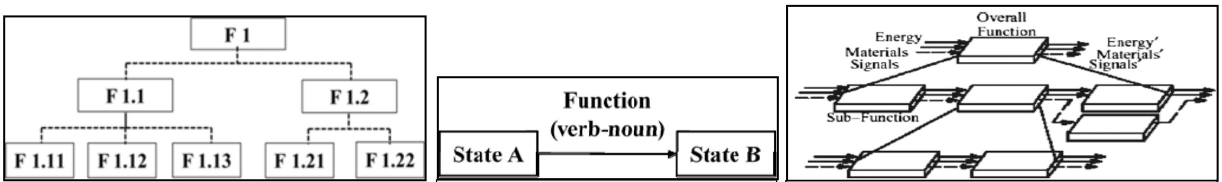
The two key modelling aspects, functional and structural basis, have their pros and cons. In practice and in literature [3, 4, 8], it is observed that both aspects are applied in product development and systems engineering organizations. On the one hand, the product architects take interest in solution dependent analysis, where they look at the linkages, attributes and interface relations between the decomposed parts. The functionalists define and analyse the functionalities of the product on the other hand. This paper proposes a concept that aims to capture the information of both solution independent and dependent analysis in a single framework in a coherent and structured manner using a multiple-domain approach.

2. Literature review of product modelling frameworks

A number of product modelling frameworks have been developed over the past two decades in engineering design. For readers, the comprehensive reviews and applications of such modelling frameworks in academic and industry are provided by [9] and [10]. In this paper, a literature of existing modelling frameworks is reviewed to highlight the different information domains. A set of requirements for integrating the solution independent and dependent analysis is thus synthesized, forming the basis of the conceptual approach in this paper.

2.1. Modelling context on functional aspect

A distinct step in function modelling approaches is the establishment of solution neutral *function structure*, which is used as basis for the subsequent design tasks to define the physical parts and structure of the product in the early stage of design [5, 11]. The basic purpose of a function structure is to organize the *functions* of a product in a coherent manner. The functional models have a variety of such function structures ranging from hierarchical tree [12] to flow oriented [5, 13–15] shown in Figure 1(a-c). In flow orientation, one function structure approach which is quite famous, shown in Figure 1(c), is the organization of functions in terms of *flows* between them: material (M), energy (E) and information (I) [5]. Another type of function structure, recently developed by [13, 14, 16] is shown in Figure 1(b), which describes the function between the two states. As a conclusion, functional models allow the possibility to identify the functional requirements and on the basis of which different concepts can be generated and evaluated.

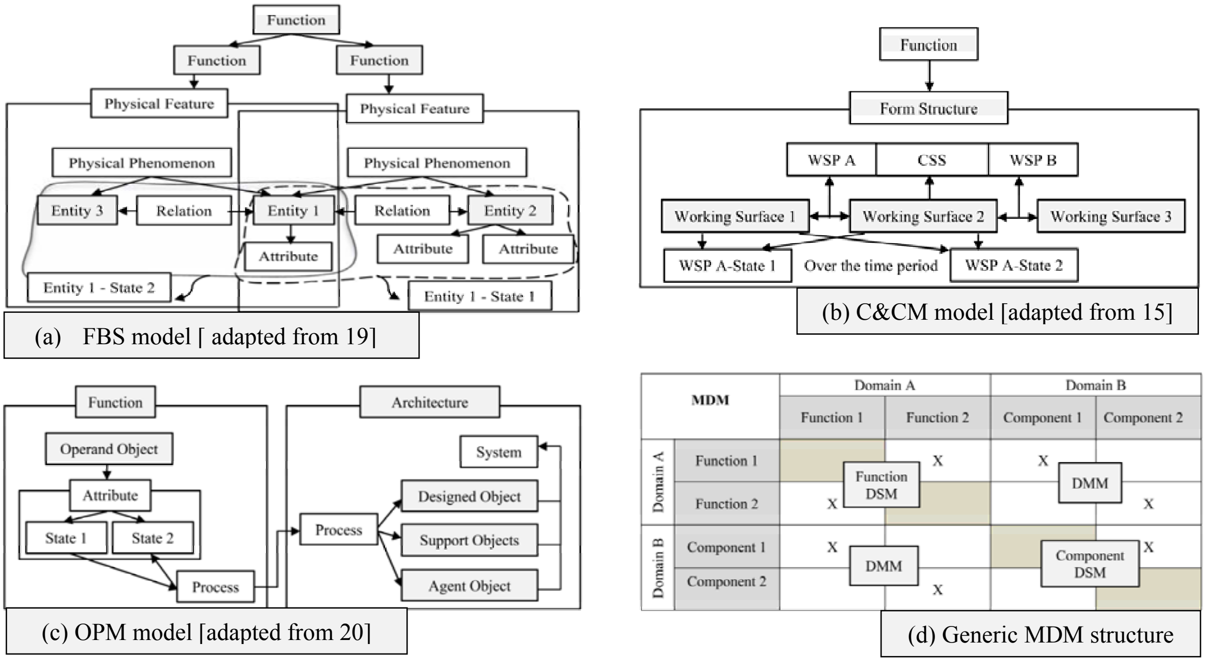


(a) Hierarchical function structure | (b) Flow-oriented | (c) Flow-oriented function structure

Figure 1. Classification of functional models

2.2. Modelling context on function to structure aspect

Function domain is the intermediary between requirement and *structural* domains. In the Axiomatic Design (AD) [17], a product is modelled hierarchically via a zigzag procedure between functional requirements and design parameters of functional and physical domains respectively. According to [17], design parameters may be *physical parts*, parameters or assemblies. However, concrete decomposition operations on the product description have not been explained [18]. Many *building blocks/elements* such as physical features in Function-Behaviour-State (FBS) model [19], object and process elements in Object-Process Methodology (OPM) [20] and working surface pairs and channel support elements in Contact & Channel Model (C&CM) [15] have been introduced for function to structure *mapping* as shown in Figure 2(a-c). The concept of working principles [5] has also been established to search for conceptual solution via morphology matrix that could satisfy the developed function structure, a network of functions and flows. The key reason behind such diverse building blocks is that a group of researchers believe, particularly related to artificial intelligence (AI) [19, 21, 22], that functions and parts alone are not sufficient in conceptualizing the product design and thus introduced another notions such as *behaviour* and *state* that exist between functions to parts mapping. Many cross-domain matrix approaches, such as Domain Mapping Matrices (DMM) and Multiple-Domain-Matrix (MDM) in [23–25], shown in Figure 2(d), have been developed to model the interactions between functions and parts of a product. As a conclusion, the above approaches strongly define and represent product with different building blocks, domains, *and* support product analysis in the context of function to structure mapping.



(a) FBS model [adapted from 19]

(b) C&CM model [adapted from 15]

(c) OPM model [adapted from 20]

(d) Generic MDM structure

Figure 2. Classification of function to structure modelling approaches

2.3. Modelling context on structural aspect

In literature, a DSM approach is widely recognized to model the product in a single domain. Looking at the physical domain of a product, a DSM approach decomposes the product into its parts/components and represents its architecture by capturing *interactions/relationships* between the components [6]. In a traditional DSM, shown in Figure 3(a), a relationship between two components is described via a qualitative *scheme* such as ‘x’ or quantitative number e.g. ‘1’. However, this sort of representation does not describe multiple interactions as realized by researchers in [3, 26, 27]. According to [28], the relationships or exchanges between two components can be of *diverse* nature. The importance of DSM based decomposition of a product and its integration analysis, underpinned by clustering technique in an industry practice, has been highlighted by Pimmler and Eppinger [3]. They used static DSMs to identify and examine alternative product architectures. Pimmler and Eppinger [3] describe four types of interactions referred as spatial (S), material (M), energy (E), and information (I) between the two interacting components along with the quantification scheme that facilitates weighing interactions among them, shown in Figure 3(b). Jarratt [4], looking from engineering change management perspective, also used the concept of S/E/M/I interactions between two interacting components but with addition to multiple-type *linkages* definitions with steady and dynamic states, shown in Figure 3(c). Campean et al [28], looking from product function analysis perspective in physical domain, characterized the exchange nature between two subsystems/components into four: physical (P), and M/E/I. They also considered internal and external interfaces in the interface matrix (IM), shown in Figure 3(d). They argued that there may be several

IOP Conf. Series: Materials Science and Engineering **65** (2014) 012005 doi:10.1088/1757-899X/65/1/012005

functional requirements associated with just one type of exchange in an interface and such requirements can be documented in tabular format. Martin and Ishii [27] used the concept of specification flows in the product platform architecture. They introduced two indices to develop the decoupled architecture: a generational variety index for analyzing generational change and the coupling index to analyse impact of changes in components. In their component-based DSM, an interface is characterized by specification flows that seem to represent a combination of flowing attributes and parameters, shown in Figure 3(e). As a conclusion, a product is modelled via DSM on structural basis with diverse exchanges and representations in its components.

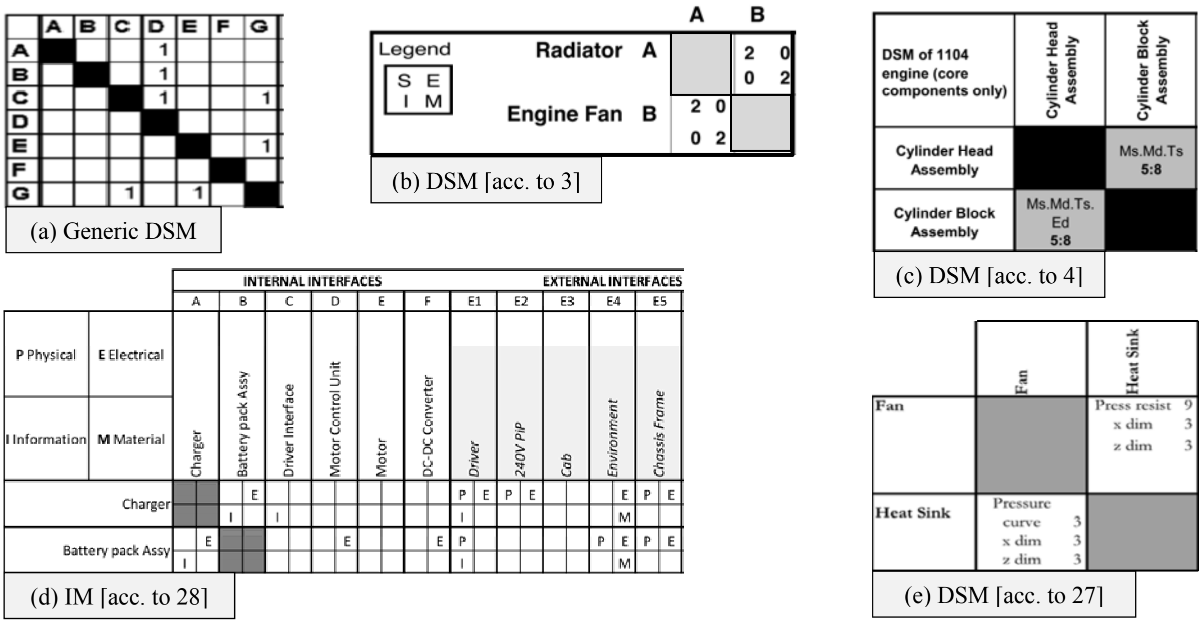


Figure 3. Classification of structural models

3. Analysis and critique of state-of-the-art

A number of product modelling approaches have been discussed in previous section in the context of functional, function to structure mapping, and structural domains. There are a number of commonalities in the modelling approaches. For instance, the concept of multiple flows or exchanges i.e. E/M/I between functional and structural elements is quite distinct as discussed in Section 2. Furthermore, it is also observed that many building blocks and tools have been established and introduced for mapping and describing the relations from function elements to structure elements for conceptualising the product. Theories like AD, C&CM, and OPM, on the one hand, support the product evolvement between different levels, whilst rule-based approaches do not, e.g. FBS. On the other hand, cross domain matrix approaches support the product analysis process but do not support design solutions search and synthesis activities based on functional domain.

The application of product modelling approaches have been widened over the past decades. However, such modelling approaches involve many complex notions, representational elements, and tools for product modelling that practitioners and industrial engineers still often find hard to implement and grasp. One of the critical reasons is the management and tracing of a product's complex information in various tools from solution independent to solution dependent analysis and vice versa. One visual approach that is considered very powerful and helpful in representing the product modelling information of many domains is the Multiple-Domain-Matrix (MDM), shown in Figure 2(d). The applications of MDM approach has continuously increased over the last few years in product design [25], process optimisation and modelling [29] and management of product development project [30] and is also considered in this paper for product architecture analysis.

As an overall conclusion, the discussed methods are valuable in different phases of product design. However, the existing methods still lack to deliver a straightforward analysis and comprehensive integrated solution independent-dependent analysis. To summarise, no current approach exists that provides the information of both solution independent and dependent analysis in a *single tool, and that also takes into consideration* the following issues;

- To *balance* the design effort both across solution independent and dependent analysis
- To deliver a *process* based on existing but minimum tools that are utilised in current practice for product decomposition and synthesis
- To establish a structured, coherent and *common linkage* between solution independent and dependent analysis for the *integration* purpose
- To support the consistent knowledge transferability between functionalists and architects

This paper proposes an integrated approach for complex product architecture analysis starting from solution-neutral to solution dependent analysis based on tools existing in literature.

4. Proposed Approach

The process for the proposed integrated approach is presented, on left side of Figure 4. The approach is based on two key phases: solution independent and dependent phases. The tools' sequence and information flow for the integration of both phase analysis is shown, on right side of Figure 4.

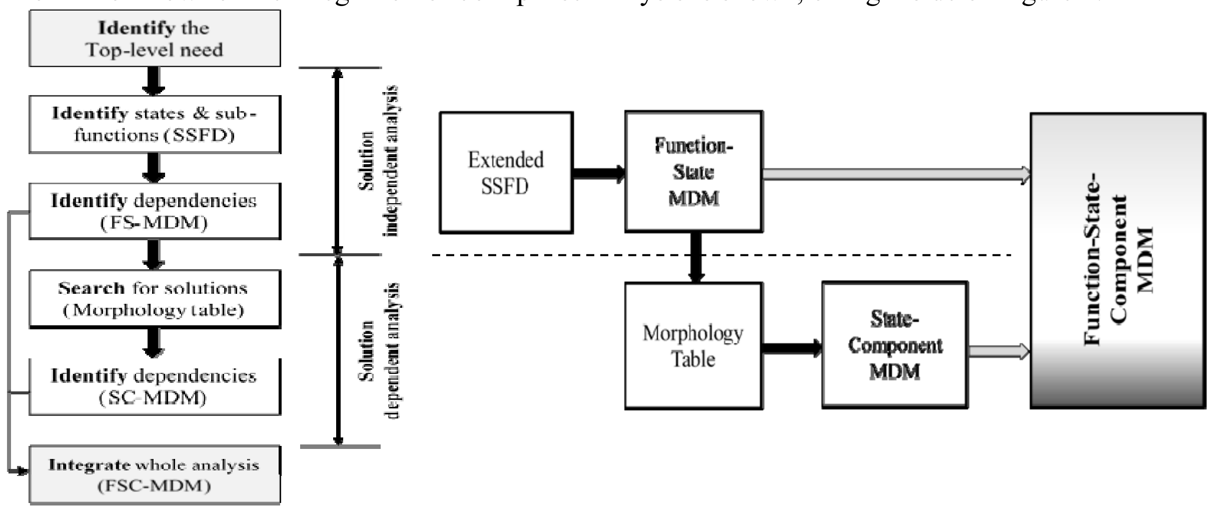


Figure 4. Proposed integrated approach process structure and information flow

The working of the proposed approach is discussed in this section, followed by its illustration with a case study in the next section.

4.1. Solution independent analysis phase

The solution independent phase is based on two key tools: System State Flow Diagram (SSFD) and Function-State (FS) MDM. The product definition and architecture analysis starts with solution independent stage underpinning a tool known as SSFD, introduced for the first time in [12] and discussed in detail in [13]. It is then followed by FS-MDM tool comprising of function DSM, state DSM and two FS-DMMs, driven by SSFD. Here, an SSFD is adapted to some extent by involving *constraint* elements on states' attributes. A distinct feature of SSFD is its ability to describe a main flowing object's states transition based on graphical representation. The solution independent MDM analysis is conducted on the modelling concepts and framework given by [23], however, the elements of our functional model are slightly different, particularly in the context of their *operation* and our *function* definition. Moreover, the interfaces in their [23] MDM between the domains are represented via qualitative and quantitative schemes such as mark 'x' and values ranging from 1-3. Our approach involves input-output flows specifications in the state-DSM interfaces and by keeping the same qualitative scheme in function-DSM in the solution independent MDM.

4.2. Solution dependent analysis phase
Once the functionalists complete the SSFD analysis and transform the knowledge into FS-MDM, it is then transferred to architect's team that explore the solutions and perform solution dependent analysis. In this phase, there are again two key tools available to engineers: the morphology table and the State-Component (SC) MDM. The state DSM within SC-MDM remains same as in the stage of solution independent phase whereas the interfaces between component DSM are represented via four types of interactions i.e. P/M/E/I with their flows exchanges and specifications.

In the end, the knowledge of both phases is integrated into a single framework named as Function-State-Component (FSC) MDM, shown in Figure 4's right side, which represents the whole product architecture in a structured manner. State domain is the linkage which is common between solution independent and dependent analysis. In the final FSC-MDM, this domain helps the architects to know components' capabilities in terms of delivering the desired input-output flows and in what capacity they interact with each other in terms of flows and spatial specifications. For the functionalists, the FSC-MDM manages to identify the required functions for states transition and the dependencies between functions. It can be observed that equal number of tools are available for both phases: the SSFD and FS-MDM tools in solution independent phase and the morphology table and SC-MDM tools in solution dependent phase.

5. Case Study
A domestic scale solar robot toy (SRT) multi-disciplinary case study is selected for illustrating the proposed framework. To keep the study simple, a specific unit (such as wave arm or leg) in SRT has been considered for analysis. Solar energy powers the SRT solar board and is absorbed via thermal collectors, and this energy is then used to drive mechanical systems. The SRT receives solar energy as an input and generates rotational energy to rotate its arm/leg as an output. In order to illustrate the process and to keep the case study 'simple', only the *energy flow* mechanism is considered here.

5.1. Identifying the top level need
At desired abstract level, the top function of SRT is 'convert solar energy into rotational energy' in order to rotate the robot arm full 360^0. It is represented by an extended-SSFD format comprising of constraint conditions in Figure 5.

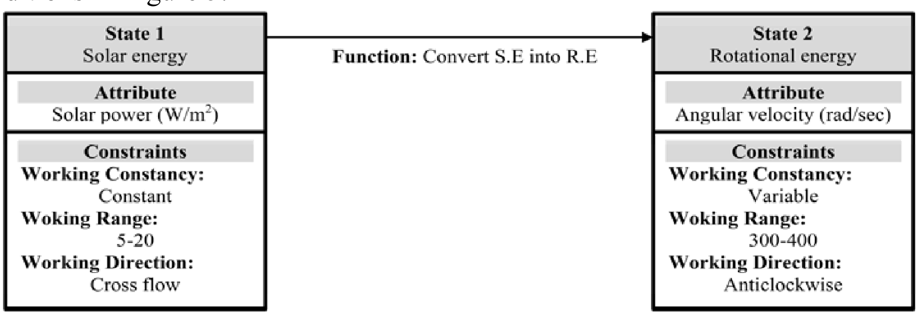


Figure 5. SRT high level representation via extended SSFD

5.2. Solution independent analysis

5.2.1. SSFD tool: high level function decomposition
The design team can decompose the high level function into sub-functions with the identification of intermediate states as shown in Figure 6. The functionalists at this stage perform many iterations for function structure development, thereby identifying intermediate states and corresponding functional requirements. Finally, the functionalists agree to the iterated function structure shown in Figure 6.

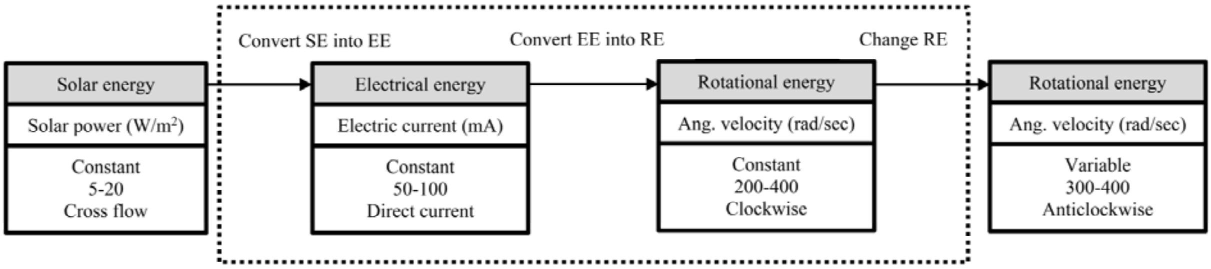


Figure 6. The main flow representation with sub-functions via SSFD

5.2.2. Knowledge transformation into FS-MDM

The knowledge from SSFD is then transformed into FS-MDM. In the FS-MDM, functional interfaces become visible while divorcing the states from functions. Moreover, flowing objects in state domain are also divorced from functions and their interfaces are also identified and managed in terms of input-output flows specifications.

5.3. Solution dependent analysis

After the solution independent analysis, the designers search for solutions that could satisfy the identified functions and relevant input-output states.

5.3.1. Morphology table

A morphology table, built-on function-state and constraint knowledge, is used to provide the feasible solutions, shown in Figure 7. The relevant solutions are adopted and taken forward for detail analysis.

Functions	States		Attributes		Constraints						Solutions
					Constancy		Direction		Range		
	I	O	Input	Output	I	O	I	O	I	O	
Change R.E	R.E	R.E	Ang. vel (rad/s)	Ang. vel (rad/s)	Constt	Constt	CW	ACW	[R]	[R]	Gear Pair Box
Change R.E	R.E	R.E	Ang. vel (rad/s)	Ang. vel (rad/s)	Constt	Var.	CW	To and fro	[R]	[R]	Crank Rocker
Convert E.E to R.E	E.E	R.E	Current (mA)	Ang. vel (rad/s)	Constt	Constt	DC	CW	[R]	[R]	DC-Motor
Convert E.E to R.E	E.E	R.E	Current (mA)	Ang. vel (rad/s)	Constt	Var	AC	CW	[R]	[R]	AC-Motor
Convert S.E to E.E	S.P	E.C	Solar p. (W/m^2)	Current (mA)	Constt	Constt	Cross flow	DC	[R]	[R]	Solar Board

Figure 7. Morphology table

5.3.2. Knowledge transformation into SC-MDM

The identified solutions are then placed in SC-MDM according to states input-output flows. This MDM helps the designers to capture the interface nature between the two components rather than brainstorming. The designers have to search for spatial or physical specifications between the interacting components.

5.4. Analysis in single framework

The FS-MDM and SC-MDM analysis are then combined in the FSC-MDM to provide a structured and coherent information flow from function to structure domains for product architecture. The whole architecture of SRT at system level, based on SSFD and morphology table, is transformed in FSC-MDM framework shown in Figure 8.

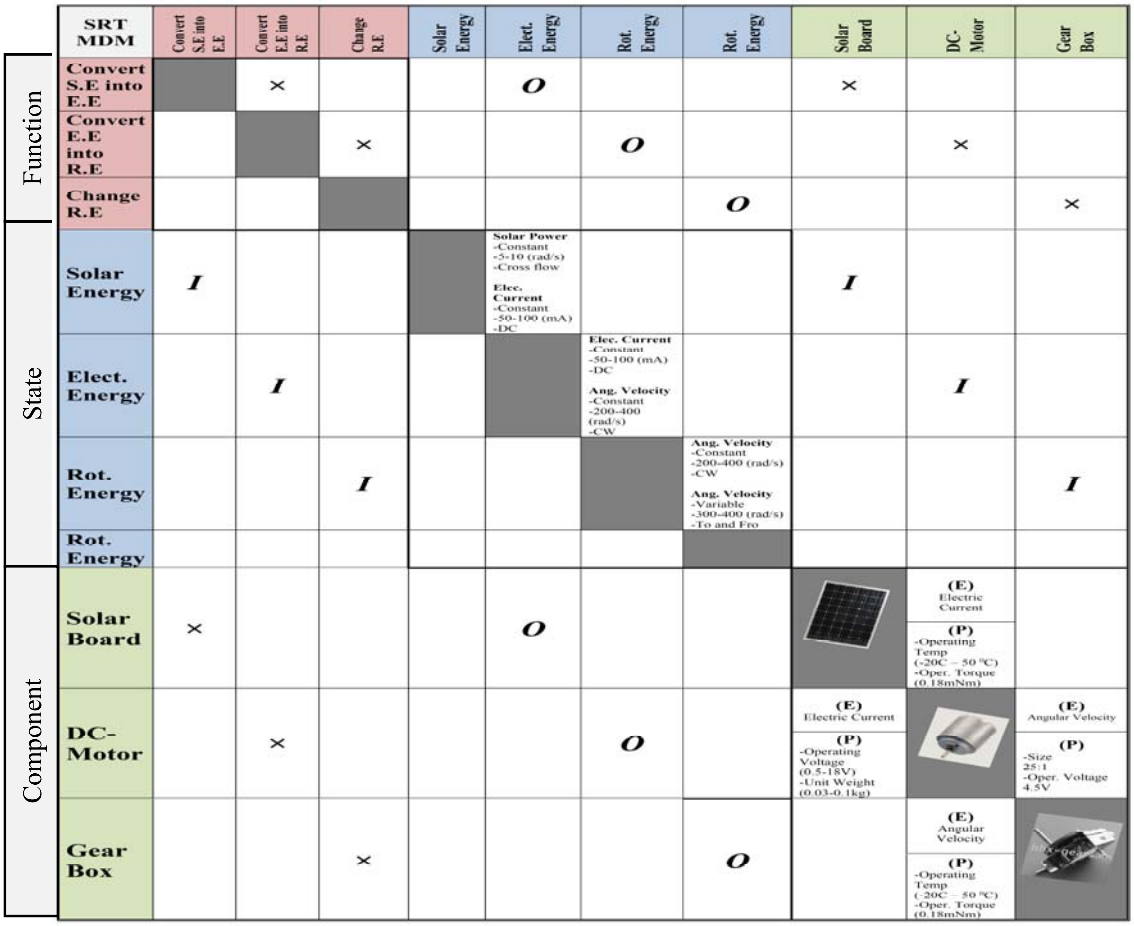


Figure 8. SRT architecture via integration of solution independent and dependent analysis

6. Approach Benefits and Limitations

As shown, the proposed approach meets its objectives highlighted in Section 3. The final MDM shows consistent information in a way that functional and structural elements share same form of input-output flows specifications. The state domain is the key linkage, binding the function and component domains in a coherent and structured manner. An application of the approach is also discussed from engineering change management and solution generation perspectives in the following paragraphs.

The functionalists and architects can both trace the changes from top-down and bottom-up in FSC-MDM. Firstly, from bottom-up, the exchanges between components are based on functions and states information rather than brainstorming. DC-Motor and Solar Board, both coupled, share electric current (energy flow) in which the current as an input to DC-Motor and output from Solar Board. Secondly, the same DSM shows that DC Motor *provides* specifications information to solar board and Gear Box or, inversely speaking, Solar Board and Gear Box *require* the specific information from DC-Motor such as operating voltage, motor weight, and motor size. This managed information helps the designers to visualise if they change or replace DC-motor then which specifications need to be carefully handled for other components. Any change in DC-motor will cause the solar board to change to meet the DC-motor specifications and similarly it will also impact on the corresponding functions and states all the way up. This distinct feature is observable in Figure 8. Hence these two sorts of interfacing management features (i.e. exchanges and specifications) in components DSM also help not only for final concept design but also for assembly design or change management.

Secondly, from top-down, if any functional requirement is changed at the top level then it will also impact all the way down to components and the interfaces between them. For example, the product architecture based on following components i.e. *Solar Board+DC-Motor+Gear Box* was selected as a final concept design. Now assume if the top level functional requirement associated with arm rotation is changed from 360^0 rotation to 0-180^0. Moreover, it should return back from 180-0^0, then the design team will look for another solution, e.g. 'Crank Rocker' from morphology table (see Figure 7) that meets the same sub-functional and states requirement but with different-constraint conditions, as it provides 'to and fro' motion. In that case, the product architecture design concept would be *Solar Board+DC-Motor+Crank Rocker* and it will require the designers to manage the specifications and interfaces between components accordingly. Thus, the proposed approach integrates solution independent and dependent analysis in a structured way.

Though the approach serves its primary objectives, however it has some key limitations which are discussed and considered for future work. The proposed approach has a systematic structure, however, it results in establishing and completion of large matrices. The input-output is described with only one attribute and its constraints. According to SSFD [13], a state is a generic object which can be described by a set of measurable attributes. In the proposed approach, a state domain is used as an intermediary and mapping element from functions to structures. The current approaches such as FBS, C&CM, and OPM offer many structured building blocks for function to structure mapping and recently, MDM-based approach also include behaviour domain within the function and structure domains [31]. The customer/market requirements are also not captured in the proposed approach. These limitations would be considered for future work.

7. Discussion and Conclusions

The main aim of this paper was to develop an integrated and structured design approach for complex product architecture in the context of solution independent and dependent analysis based on tools that are currently practice. The review of current methods and tools as well as the importance of product functional and structural modelling in the academic and industrial practice pointed out the need for the proposed approach. The proposed framework is built-upon the adaptations of principles of SSFD, morphological table and MDM tools. The SSFD tool helps for functional decomposition, morphological table for searching solutions and MDM for design architecture synthesis. The framework provides a systematic and balance procedure to perform both solution independent and dependent analysis. A core binding linkage between the function and structure domains is the state domain that keeps the information in a way that both functional and structural elements share same sort of input-output flows specifications.

The Solar Robot Toy case study illustrates the working of the proposed integrated approach. The approach strengths are also highlighted with the SRT case study in the contexts of identifying and comparing various solutions at same abstraction level and from engineering change management. The framework can be applied in various decomposition levels. The proposed approach is easy to understand and it employs the minimum graphical tools that help in improving the communication between functionalists and architects.

References

[1] Uddin A et al 2013 Function-based conceptual design expert (CDE) systems *Int. Conf. on Adv. in Mech and Manu. Engg.* Kuala Lumpur Malaysia
[2] Chmarra M K et al 2008 Revisiting the divide and conquer Strategy to deal with complexity in product design *IEEE/ASME Int. Conf. on Mechatronic and Embedded Systems and Application*
[3] Pimmler T U and Eppinger S D 1994 Integration analysis of product decompositions *ASME Design Theory and Methodology Conference*, September Minneapolis
[4] Jarratt T A W 2004 A model-based approach to support the management of engineering change PhD Thesis University of Cambridge, UK
[5] Pahl, P et al 2007 *Engineering design a systematic spproach* (Springer).
[6] Browning T R 2001 Applying the design structure matrix to system decomposition and integration problems a review and new directions *IEEE Transactions on Engg. Management*, vol 48 no 3 pp 292-306

[7] Danilovic M and Browning T R 2007 Managing complex product development projects with design structure matrices and domain mapping matrices *Int. J. of Project Management* vol 25 no. 3 pp3 00-314

[8] Campean et al 2013 Systems engineering excellence through design an integrated approach based on failure mode avoidance *SAE Int. J. Mater. Manf.*, vol 6 no 3 pp 389-401

[9] Tomiyama et al 2009 Design methodologies industrial and educational applications *CIRP Annals - Manufacturing Technology* vol 58 pp 534-565

[10] Lopez-Mesa B and Nicklas Bylund 2011 A study of the use of concept selection methods from inside a company vol 22 no 1 pp 7-27

[11] Ulrich K T and Eppinger S D 1994 *Product design and development* (McGraW Hill)

[12] Campean I F and Henshall E 2008 A function failure approach to fault tree analysis for automotive systems *SAE International Technical Paper* no 2008–01-0846.

[13] Campean I F et al 2013 A structured approach for function based decomposition of complex multi-discipinary systems *Proceedings of the 23th CIRP design conference* pp 113-123

[14] Albert A and Christian Z 2011 Interdisciplinary systems modelling using the contact and channel model for SysML *International Conference on Engineering Design*

[15] Albers A et al 2003 Engineering design in a different way : cognitive perspective on the contact and channel model approach *Visual and Spatial Reasoning in Design* pp 1-21

[16] Goel A et al 2009 structure behavior and function of complex systems The structure behavior and function of complex systems

[17] Suh N P 1998 Axiomatic Design Theory for Systems *Research in Engineering Design* pp 189-209

[18] Komoto H and Tomiyama T 2011 A theory of decomposition in system architecting *International Conference on Engineering Design*

[19] Umeda Y et al 1996 Supporting conceptual design based on the function-behaviour-state modeller *Artificial Intelligence for Engg Design, Analysis, and Manuf.* vol 10 no 4 pp 275-288

[20] Dori D 2002 *Object-process methodology a holistic systems paradigm* (Springer Berlin Heidelberg)

[21] Gero J 1990 Design prototypes a knowledge representation scheme for design *AI Magazine*, vol 11 no 4 pp 26-36

[22] Christophe et al 2010 RFBS A model for knowledge representation of conceptual design *CIRP Annals - Manufacturing Technology* vol 59 no 1 pp 155-158

[23] Deubzer F and Lindemann U 2009 Product architecture definition and analysis using matrix-based multiple-domain approach *Proceedings of ASME IDETC/CIE* pp 1197-1205

[24] Maurer M and Lindemann U 2008 The application of the multiple-domain matrix pp 2487-2493

[25] Lindemann et al 2009 *Structural Complexity Management* (Springer Berlin Heidelberg)

[26] Jarratt T A W et al 2004 Development of product model to support engineering change management *Proceedings of TMCE* April Switzerland

[27] Martin M V and Ishii K 2002 Design for variety developing standardized and modularized product platform architectures *Research in Enggg Design* vol 13 pp 213-235

[28] Campean et al 2011 A structured approach for function analysis of complex automotive systems *SAE Technical Paper* no 2011–01-1268 pp 1-14

[29] Konig et al 2008 Multiple-domain matrix as a framework for systematic process analysis 10^{th} *Int. Design Structure Matrix Conf.* November Stockholm Sweden

[30] K. Oizumi et al 2011 Management of prod. development proj. through integrated modeling of product and process information *International Conference on Engg Design,* Denmark

[31] Hamraz B et al 2013 Requirements-based development of an improved engineering change management method *Journal of Engineering Design*