Formal early design synthesis of mobile work machine

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ABSTRACT: *This article introduces a formal early design synthesis and its corollary, function-behaviour-structure, to an early design analysis and identification of concept for complex systems. First, the article presents the state of the art of design modelling frameworks, tools for dynamic system synthesis and behaviour simulation. Secondly, the key elements for function-based design synthesis and behaviour modelling are discussed, as well as the interest and actual limitations of the general architecture model applied to early design of complex systems. Finally, the article proposes an alternative approach in order to allow systematic design and to explore behaviours of functions and structures early in the development stage with the intention of future coding as a computational tool to allow design automation.*

KEY WORDS: *function-base design, complex system, behaviour, design synthesis, early design, design automation*

1. Introduction

Early phase of design is the most crucial part of the whole design process and the intention of the adjoining analysis is to explore the best alternative design solution for the targeted product (Horváth, 2000). The importance of this design phase is emphasized when the complexity of the product (hereafter referred as system) increases.

Rechtin (2000) defined a system as a collection of different elements that together produce results not obtainable by the elements alone. The results include system level qualities, properties, characteristics, functions, behaviour and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationships or interconnections among the parts.

The complexity of a system rises just from these interconnections between parts. Complexity is found in the functions, organs and structure but also in the design process of a system. Understanding and managing the complexity is important because it can provide a powerful tool to augment the creativity of the designer. Engineers' intuitive understanding of this concept has, until recently, been sufficient for the practice of engineering.

In order to cope with this complexity, designers traditionally use design strategies that consist of recycling existing knowledge to solve new problems, simplifying the problems, and applying the concept of search and satisfaction (Simon, 1997). In spite of these cushioning strategies the creation of complex artefacts inevitably results into an increasing design process complexity (Carayannis, *et al.*, 2007).

Design of complex systems like mobile work machines (MWMs) is at present, with some exceptions, done almost solely through recycling the existing systems architectures inherited from decades before. The drawback of this is the increased design complexity because of various options as subsystems, high number of dynamically interacting components and increased nonlinear relations between them (Carlini, *et al.*, 1997; Emadi *et al.*, 2005; Chan, 1993, 2002). Another drawback stemming from complexity is the fact that if traditional conceptual design methods are applied to this kind of systems, they produce abstract or incomplete solutions that are unable to satisfy the design needs if these are exactly defined from all functional, constraint, and performance views.

The relationship of conceptual design in complex system development has to move to a higher level of abstraction. If early design phase is reduced to creative group meetings and activation of experiences, it does not allow adequate use of formal tools, methodologies, and analysis at this crucial phase of design process.

Due to the clear restrictions of traditional design strategies, managing the design of complex systems calls for a robust and systematic approach to be used early in the design phase. One possible starting point in creating this approach could be model-based design which combines the power of models, qualitative processes, quantitative processes, and computers.

Computers provide great support in engineering calculation tasks, but they also possess great potential for helping with reasoning tasks. In recent years, the prospect of computers taking on more and more of the reasoning tasks involved in engineering design has placed a premium on being explicit and precise about many of the intuitive concepts related to design. These are concepts such as function, behaviour, structure, and causal relations. With increase in complexity and multidisciplinary design, the development of a general framework will greatly enhance computer assistance with reasoning tasks in engineering design (Chandrasekaran *et al.,* 2000).

The present article begins with exploring the state of art of design frameworks, and tools for dynamic system synthesis and behaviour simulation. Next, a model framework for early design analysis and concept generation is proposed. The authors present a formal early design synthesis, an integrated model of function-based design synthesis and a function-behaviour-structure with the intention of future coding and implementation with computational language tools like SysML and Modelica. The following section shows an implementation of part of the proposed model in a case study. The final section discusses the advantages and limitations of this approach.

2. State of the art

2.1. Motivation

One foundation of engineering design is generation of concepts which provides a basis for designers to apply creativity and contribute their personal knowledge and experience. It also represents the choice or development of technology and innovation to fulfil the customer’s needs. Until recently concept generation has been fundamentally informal and has been considered art, not formal or science. Thus the tools for concept generation have been based almost entirely on experience and intuitive understanding (Wood *et al*., 2001).

Methods are however constantly being developed, tested and implemented, and at the present various design developing tools are available for concept generation (Otto *et al*., 2001). A simple view of these methods is as shown in Figure 1.

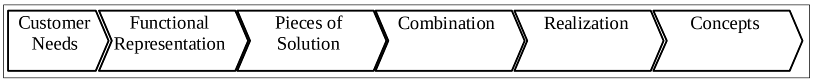

Figure 1. *Simplified view of developing tool for design concept*

The question now arises if this developing tool set is complete and converging. If the emerging new formal methods were applied to product concept generation, it would be to formalize that which was informal, systematize that which was thought to be purely artistic, and understand that which was labelled as innate creativity (Wood *et al*., 2001). The purpose of this article is to convey and advance an early design tool set, referred to as "formal early design synthesis" for complex system design.

The emphasis in this article is not just concepts generate based on the traditional method, but to formalize the process. Formal early design synthesis seeks to produce innovative solutions guided by theories and principles. Based on the formalization, it is the intention in the future that the process may be coded, at least significantly as a computational method.

2.2. Background to formal early design synthesis

Since all the requirements for a system are not clearly defined at the onset of a design process, conceptual or early designing involves finding out what is needed and whether these needs are expected to be altered during the course of the design process (Gero *et al*., 2004). Design exists in order to deliver systems that have desired functionalities. The concept of function is thus fundamental in system engineering practice.

The basic assumption in design processes is the existence of three classes of variables, namely function variables, behaviour variables, and structure variables (Gero, 1990). In early phase of design the customer needs or requirements for a system are abstracted to formulate a structure variable which satisfies these requirements. The design of a system should then contain functions that in turn satisfy the characteristics embedded in structure variable. Thus one attribute in design processes is to concentrate on what the entities do before determining what the entities are (Blanchard *et al.*, 2006).

Terminologies used in this article are defined as follows for clarification (Antonsson *et al.*, 2001).

-*synthesis* is the composition of fundamental elements into combinations that produce unique and desired results.

-*design synthesis* is a non-analytical flexible approach that includes the determination of the elements of a given design, and the ability to reapportion and reconfigure existing elements and to create new ones. It is the reverse of analytical processes.

-*formal,* in this context indicates that the process is founded in a theory, set of theories, or set of principles and is computable, structured, and rigorous, not an ad hoc.

2.3. *Early design modelling framework*

Use or design of a system is triggered by a need or desire felt by some human in some context. The identification of a need is followed by function, behaviour, and then structure.

A central meaning of function is *function as* (*desired or intent*) *effect*. The description of functions is often in terms of the device's properties or behaviour, without any explicit mention of what the device might help achieve in the world outside it. Thus, this description is from a *device-centric* or an *environment-centric* viewpoint, or even in a mixture of the two viewpoints. The concepts of function and behaviour are symbiotic. The term *behaviour* refers to the value(s), or relations between values, of state variables of interest at a particular instant or over an interval of time and the causal rules that describe the values of the variables under various conditions (Chandrasekaran et al., 2000).

Objects, fields, flows and flow substances, actions, events, properties and causal connections are just a few of the elements of the ontology of a system. A new object is created by composing some objects into a larger configuration. The specification of the objects in the configuration and the structural relations between them is called the *structure* of the configuration. Structure defines the basic interaction framework, within which other, temporary, interactions take place.

When analyzing the interactions between function, behaviour, and structure variables in a design process, a formal representation is usually needed. One possible framework is the Function-Behaviour-Structure (FBS) model by Gero (1990) which represents design by a set of processes transforming function variable first to behaviour variable and then to structure variable (Figure 2).

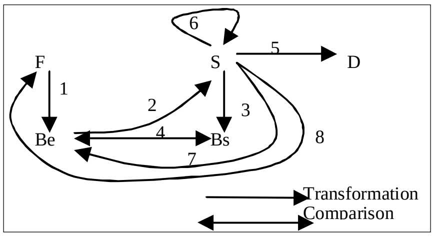

Figure 2.*Gero´s FBS model (Gero, 1990)*

The eight processes represented in the FBS framework are claimed to be fundamental for all design and are briefly summarized as:

Step 1. *Formulation:* transforms the design problem, expressed in function (F), into expected behaviour (B_e) to enable this function.

Step 2. *Synthesis:* transforms B_e into a solution structure (S) intended to exhibit this desired behaviour.

Step 3. *Analysis* (process 3) derives the “actual” behaviour (B_s) from the synthesized structure (S).

Step 4. *Evaluation* compares B_s with B_e to prepare the decision if the design solution is to be accepted.
Step 5. *Documentation* produces the design description (*D*) for constructing or manufacturing the product.
Step 6. *Reformulation type 1* (addresses changes in the design state space in terms of structure variables or ranges of values for them.
Step 7. *Reformulation type 2* addresses changes in the design state space in terms of behaviour variables or ranges of values for them.
Step 8. *Reformulation type 3* addresses changes in the design state space in terms of function variables or ranges of values for them.

Gero and others (Gero *et al.*, 1992, 2004) stipulated that the formulation step *1* is supported by *experiential knowledge*. Designers carry out this formulation step based on their experience through prototype-based designing. The step between function, behavior and structure description is at a micro level, based on subsequent actions by the designer. A simplified FBS-model indicates that the transition from intentional description of an artifact to a structural description is not located in one-step in particular but divided over both the formulation and synthesis steps.

Gero (1990) defined function as the design intentions or purpose, behaviour as how the structure of an artefact achieves its functions and structure as the components that make up an artefact and their relationships (Vermaas *et al.*, 2007). By these definitions, the functional descriptions of an artefact are intentional theoretically and structural descriptions are purely structural. Furthermore, the definition allows that behaviour can be either structural or intentional. These definitions have been refined lately but the changes in the definition of function are more or less still intentional.

There is a clear indication that the conceptual framework underlying the FBS-model is fuzzy (Gero et al., 1992). There is a clear discontinuity in the FBS model and the comparability of the expected behaviour (Be) and structured behaviour (Bs) is difficult. Consequently, developing a model to enhance unambiguous continuity of the early design process is a necessary condition to ensure a formal design procedure.

2.4. Formal function-based synthesis

The area of function-based synthesis is abstracted in terms of a general architecture representing various design methods, with their input-output, their fundamental actions, and their layouts as shown in Figure 3. The architectural model illustrates a metaview of the various function-based synthesis methods and enables the analysis of the methods including their similarities and differences.

A function-based synthesis technique might begin with a functional description of a product opportunity, followed by search strategy of a database or repository and creativity to create a list of potential piecewise solutions to the function. Solutions are generated by adopting an organized solution combination.

Engineering modelling or optimization approaches is adopted to embody these solutions manually or semi automatically (Antonsson *et al.*, 2001).

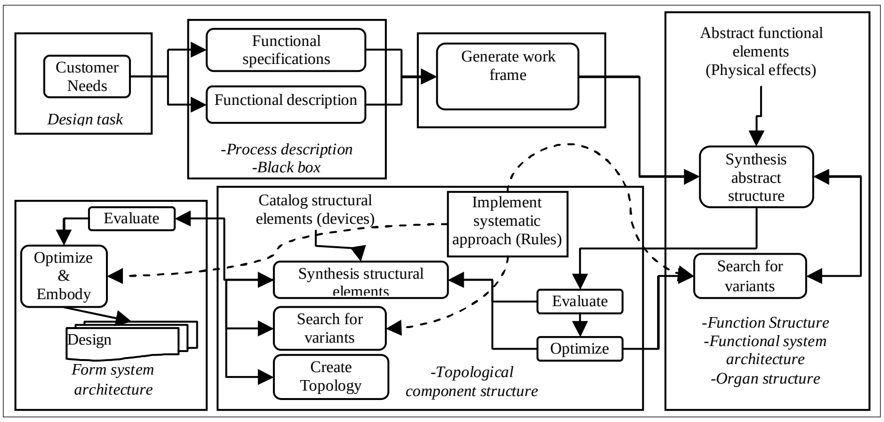

Figure 3. *Architecture model in conjunction with a superimposed design process (Antonsson et al., 2001)*

The overall process flow in function-based synthesis can be expressed as a hierarchical set of models; beginning with the customer needs and includes the following:

Functional elements are abstract representation of designs that convert inputs to outputs. These elements are arranged in an optimized fashion into the *functional system architecture* (FSA) which is a preferred functional solution to satisfy the customer needs (Wood *et al*., 2001).

Stone and Wood (2000) gave a concise methodology for Functional model derivation in the form of task division. In this initial task, a product or system is modelled abstractly as a black-box. This is a graphical representation of product function with input/output flows that allows for focusing on the greatest overall need of the system. The inputs and outputs are the major physical flows of the system, classified as energy, material, or signal (Pahl *et al.*, 2007; Otto *et al.*, 2001).

The next level of the model is the *function structure* which is a graphical, form-independent expression of the product design (Pahl *et al.*, 2007; Otto *et al.*, 2001; Hubka *et al.*, 1988; Ullman, 1993). The functions are selected from a set of standard functional elements referred to as function basis or function taxonomy (Stone *et al.*, 2000). For complex function structures, the concept of modularity may be applied to simplify them for further manipulation. Module heuristics is applied to identify the modules in a function structure by incrementally applying the modules to developed function model (Otto *et al.* 2001). At this level of abstraction, the system has a specific functional architecture to satisfy the design requirements, but has no specific physical embodiment.

Further refinement of the design leads to the *organ structure* (Hubka *et al.*, 2001). Heuristics is used to identify functional elements that can be gathered together to form functional modules (Otto *et al.*, 2001, Stone *et al.*, 2000a). This is the last level where abstract functional elements are used to describe the product. Thus, at this point, the design is fully described in terms of functions.

Structural elements or devices are selected to satisfy the input-output requirement at each node in the system. This is the next level of abstraction and it associates specific electromechanical devices with the function taxonomy used in the function structure. This level represents the topological component structure of the design and can be captured using configuration flow graph (CFG) (Kurtoglu *et al.*, 2008). A CFG follows strictly the functional topology of the system and maps the desired functionality into the component configuration domain. In a CFG, arcs of the graph represent energy, material, or signal flows, while nodes represent system components. Function taxonomy terminology is adopted for flow naming, whereas component graphs are named using taxonomy of standard electromechanical components (Kurtoglu *et al.*, 2005).

The final level in the formal function-based synthesis is the *form system architecture* which is the least abstract level in the process where the design is now fully embodied. This is the level where the various design methods, creativity, and experience of the designer(s) are used to optimize the embodiment to satisfy the design needs in the most efficient and effective way possible with the available resources.

2.5. Synthesis of dynamic systems

The common goal of formal synthesis is developing a mathematical, grammar based, or lexicon language for transforming functional representations to physical designs or products. Concentrating on the schematic description in the early stage of the design without regard to the physical description forces the designer to abstract the functional behaviour before worrying about instantiation. Ulrich and Seering (1989) define schematic description as a “graph of functional elements” and schematic synthesis as “generating a schematic description in response to a specification of desired device behaviour”.

Generated Bond graphs that are used in the synthesis of dynamic systems represent the functional relationship within a dynamic system (Paynter, 1961; Shim, 2002). Bond graphs are non-domain specific representations of the exchange of energy in a system. Systems are represented as interconnected components with power flows across their ports. The ports are specified in terms of effort and flow variables in various domains.

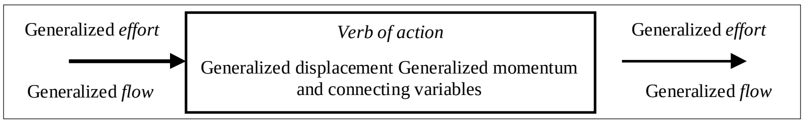

Figure 4. *Generic model of organ structure*

The effort and flow variables can be represented as generic variables that are non-domain specific, thus allowing the use of this schematic graph to describe multiple energy domains. A vision of a function combining both the intention (i.e. verb of action) and the structure (i.e. five types of generalized variables) inspired from the Bond graph theory (Shim, 2002) is shown in Figure 4.

2.6. Simulation of behaviours

The behaviour of a function or structure can be analyzed from a discrete perspective, but the analysis also requires the use of continuous modelling approach which can be modelled with Petri net. Petri net is a universal factor-process model which was developed by Petri (1962). The model consists of three structural components: places or position (factors), transitions (processes), and directed arcs. It is a bipartite, directed, and labelled graph.

A Petri net describes the structure of a discrete event of a system, while the dynamics of the system is described by its execution. The dynamic behaviour of a system or product can be represented using tokens which graphically appear as dots in places or position. Petri net has well defined mathematical foundation and a comprehensible graphical notation (Salimifard *et al.*, 2001) (fig. 7). This allows for setting up mathematical models of the system behaviour, which in turn allow for validation of the Petri net by various analysis techniques.

Colour Petri Nets (CPNs) is a specific type of Petri net developed in the Late 1970s by Jensen, (1981) which belongs to the area of discrete event system methodology. The Petri Net then becomes coloured if its tokens are distinguishable. In CPNs, tokens often represent objects (e.g. resources, goods, humans) in the modelled system and to represent attributes of these objects, the Petri net model is extended with colour or typed tokens. Each token has a value often referred to as `colour'. Transitions use the values of the consumed tokens to determine the values of the produced tokens.

A combination of Buckingham Pi theorem (1914) in dimensional analysis (Butterfield, 2001; Bashkar *et al.*, 1990) and Petri net explore generic behaviours of generic organs further. This also supports risk analysis early in the design phase to ensure robustness. Dimensional analysis is a method for reducing complex physical problems to their simplest most economical forms prior to quantitative analysis. The Pi-theorem is a formal analysis procedure for problems in which some of the independent quantities that specify the problem have fix values in all cases that are of interest and can be simplified further (Bashkar *et al.*, 1990).

3. Proposal of formal early design synthesis model

In this section, the authors present the skeletal structure of the study of functional-based synthesis and its implementation in formulating a formal early design synthesis model. After analysing the *function-based synthesis* and the *function-behaviour-structure model*, these are compared to formalize an early design model. The intention is to implement in the future using SysML modelling language and to integrate with computer applications such as Open Modelica, Simulink and CAD software. Open Modelica and Simulink can be used for building simulation models automatically from behavioural models.

3.1. Formal early design synthesis model

The function-based synthesis process architecture (section 2.4) maps into the overall design process without much emphasis on the behaviour of the product or system. On the other hand it shows a clear transition from functional elements to organ structure, to component structure, and to form or embodiment of the product (Antonsson *et al*., 2001).

The FBS-model lays much emphasis on behavioural analysis of both functions and structures (Gero, 1990). But the model is problematic. The claim that the transition from function to structure can only be made through behavior is not supported by some design analysis (Dorst *et al.*, 2005). The idea of having an intermediary concept between intentional and structural thinking is worth developing. However the design process is oversimplified with the assumption that there exists just one single intermediary concept. If one considers the designing of complex systems with several structural elements, the clean design steps from function via behavior to structure and also the process of prototype instantiation becomes more complicated (Dorst *et al.*, 2005, Vermaas *et al.*, 2007). it is not clear what the precise goals of the FBS-model are. If the model is meant to describe real world designing, then the jump from function to structure has to be incorporated in the model.

Expected behaviour is using the concept of function while derived behaviour of the structure is using the concepts of components (Dorst *et al*., 2005; Gero *et al*., 1992). Consequently simulating the expected behaviour necessitates dealing mainly with qualitative information whilst simulating the derived behaviour of a structure is done by using quantitative data. This complicates the formalization needed to allow for coding and computer application.

The function-based design process which is superimposed on the process architecture (Figure 3) is mapped onto the FBS-model (Gero, 1990) to derive a *formal early design synthesis model* (Figure 5). This design approach is based on the systematic design approach by Pahl and Beitz (2007), and on the principle of the TRIZ approach, which is to transform the specific design problem into a generic design problem that can be solved using a generic solution and later derived into a specific solution (Altshuller, 1984). This will ensure unambiguous continuity of the design process and ascertain easy comparability of expected behaviour and structural behaviour and also effortless automatic generation.

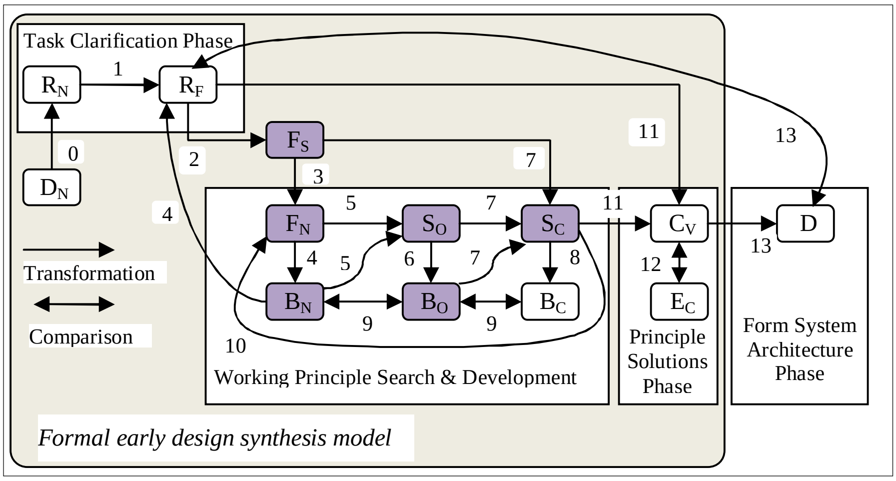

Figure 5*. Formal early design synthesis model, an integration of function-based synthesis and FBS-model*

The overall process flow in presented design model (Figure 5), can be expressed as a hierarchical set of steps beginning with the demands and wishes of the customer in the form of design needs (D_N). The design needs are conveyed as information in the form of natural language to the Task Clarification Phase (TCP). In this phase (step 0), the design requirements are abstracted to identify the essential problems and transformed to natural semantic description of the requirements (R_N). Then in step 1 R_N is formalized and transformed to formal semantic description of the requirements (R_F). From the TCP, the formalized requirement is transformed (step 2) to function structures (F_S).

The specific function structure is then conveyed (step 3) to the Working Principle Search and Development Phase where F_S is transformed into a normalized functional structure (F_N). In this transform the overall function structure is further simplified using function taxonomy (Hirtz *et al.*, 2002) and module heuristics (Otto *et al.*, 2001). In step 4, an expected behaviour (B_N) is derived from F_N and reformulated in terms of the formalized requirement. In step 5, a generic organ structure (S_O) is derived from F_N and B_N using function-based Bond graph method (Paynter, 1961; Shim, 2002; Coatanéa, 2005).

In this step a mapping between F_N and S_O is developed in order to obtain a list of generic variables (Shim, 2002; Coatanéa, 2005) which are also associated with the causality analysis of the Bond graph models. The list of variables and causality are used to model the behaviour (B_O) of S_O using dimensional analysis theory in step 6. Next in step 7 F_S is transformed to derive component structure (S_C) based on S_O and B_O. From S_C, the behaviour (B_C) of the component structure is derived in step 8. As the generic behaviour (B_O) in this model is generated stepwise from the expected behaviour and function, it allows for direct comparability to component structure behaviour (B_C) in step 9.

The search and develop operation of the design working principle is done through an iterative process as indicated with step 10. It also includes conventional design methods like literature search and analysis of existing design, intuitive methods, discursive methods, classification schemes. As according to Pahl and Beitz (2007) the principles elaborated in the subsequent phases are not concrete enough to lead to the adoption of a definite concept. Analysis in these phases is based on function structure which is aimed at the fulfilment of a technical function. Thus the developed structure components are transferred to the Principle Solution Phase where they are firmed up into concept variants (C_V) in step 11 and evaluated in step 12. A good principle solution (i.e. concept) is transferred into the Form System Architecture Phase for detail design and documentation.

4. Case study: Energy reduction in mobile work machine

In this section an example is presented to demonstrate application of the formal design model (Figure 5) to derive alternative structural architecture. In the present article, the authors are especially interested in the relevance of the fundamental elements of function-based synthesis like functional elements, organ structure, component structure and the stepwise generation of the generic behaviour. Due to space limitation, only steps 2 to 7 will be presented in this example.

MWMs employed in mining, forestry and agricultural works are generally characterized by low utilization of the available installed power. This is due to the fact that the internal combustion engine (ICE) has to be dimensioned to satisfy the maximum power demand existing during duty cycle, although the average power demand for the entire duty cycle is generally significantly lower (Carlini *et al.*, 1997). These conventional MWMs have high energy consumption and most of the energy used is not recovered. The machines include two main systems; the power train system which is classified as the Moving system in this study, and the hydraulic system classified as the Working system as shown in the energy transfer scheme during load cycle, Figure 6. The design problem is to locate the significant energy losses of the working system and reduce them.

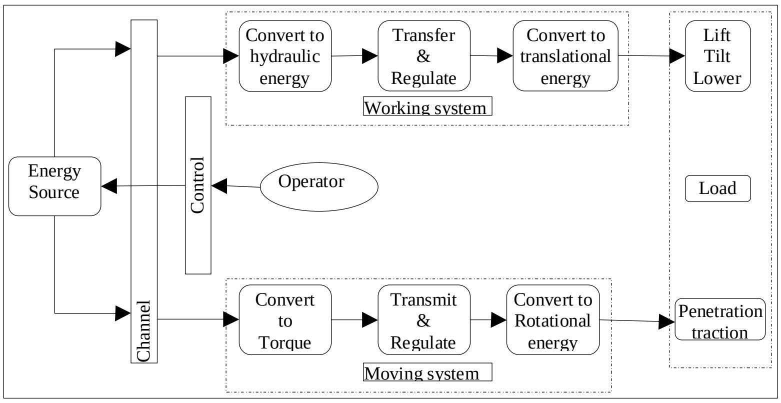

Figure 6. *Energy transfer scheme of conventional mobile working machine*

-Step 2: Establishing Function structure (F_S):
From the Task Clarification Phase (as stated, not analyzed in this article), the design problem is transferred to this level. The goal at this level is to further refine the design need in search of a preferred function solution to satisfy those needs. The MWM, which in this case is a bucket loader, must include the following functions in order to satisfy the set operational demands: 1) bucket filling, 2) bucket lifting, 3) bucket emptying, 4) bucket lowering, and 5) movement of the loader with filed/unfiled bucket for certain distances. A black box model of the MWM is as shown in Figure 7. As in the conceptual design phase, the black-box is in abstract form with the input and output flows listed more generally.

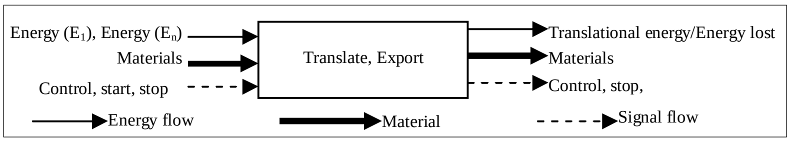

Figure 7. *Generic black box model of MWM configuration*

Due to the complexity of this machine the concept of module heuristics is applied to decompose the system. The store module, supply module, and the transfer module of the MWM (Figure 8) are investigated in this example. With these modules, the bucket lifting and lowering performances of the machine, is considered.

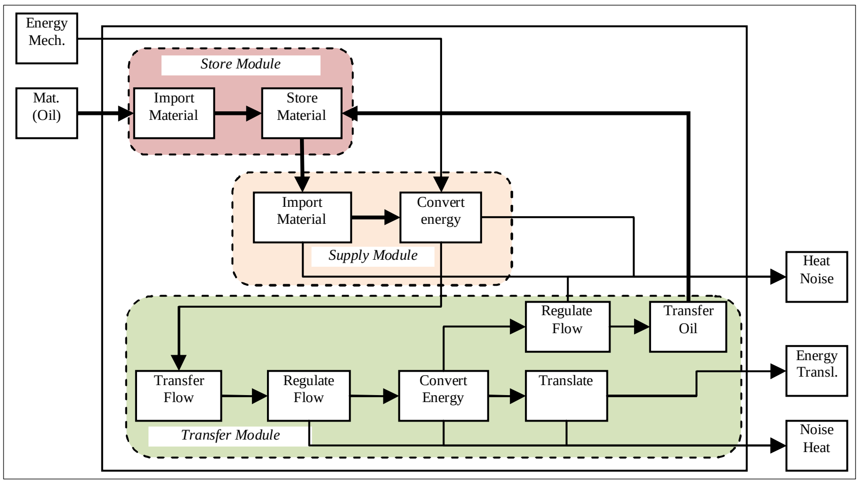

Figure 8. *Function modules of MWM´s working system*

-Step 3: abstraction from F_S to normalized functional structure (F_N)
The function modules are further refined, reconciled and simplified into a normalized functional structure (Figure 9).

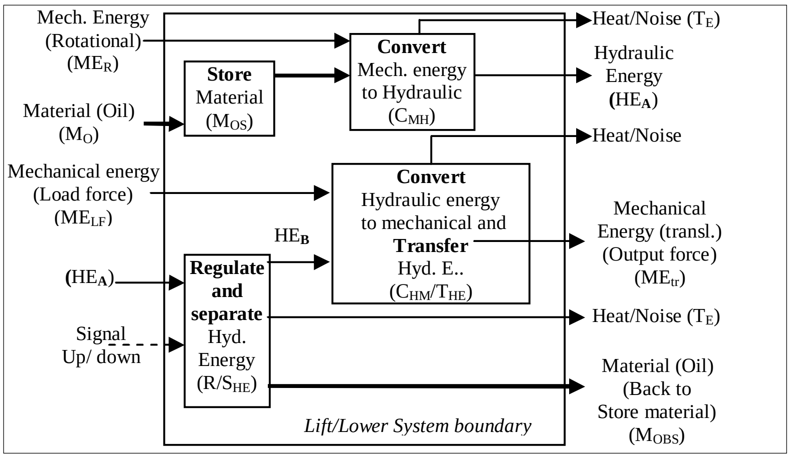

Figure 9: Normalized functional structure of MWM’s working system

-Step 4: expected behaviour (B_N) derivation from the normalized functional structure (F_N).
F_N is transformed into the B_N-model with the application of Coloured Petri-Net (CPN). In this wise, the tokens represent the type of energy, material, and signal flowing through the system. The token colours vary during propagation through the system. For instance, mechanical energy is transformed into hydraulic energy and

the hydraulic energy is itself transformed into thermal energy (heat) and acoustic energy (sound). Each type of flow is represented by a specific colour.

Thus in this way, the accuracy of connections and type of transformations taking place at the transitions can automatically be verified. The model allows taking into account the discrete time behaviour at this stage. The transitions of the CPN are associated with early qualitative description (QD) of the behaviour. Figure 10 shows the CPN model of the expected behaviour (B_N) of the function structure (F_N).

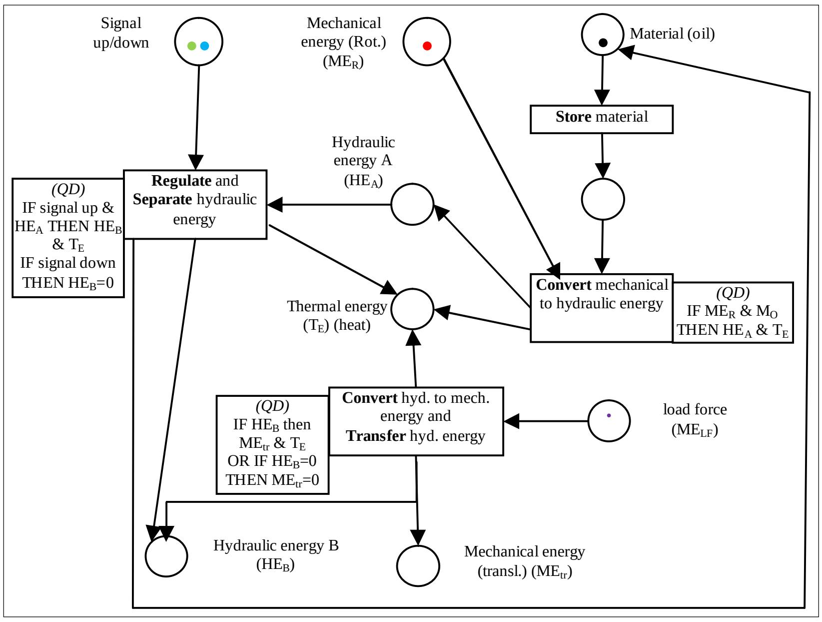

Figure 10. *CPN model of MWM's working system*

The model contains places (positions) which are representing the basic flows and the transitions which are the functions within the system boundary. The CPN model allows investigating different scenarios using Modelica as a modelling tool in future studies. It makes it possible to investigate desired and non-desired behaviours of the system and to compare different alternatives of the normalized function structure and function structure in general.

-Step 5: Transformation of the normalized function structure (F_N) and derived expected behaviour (B_N) into the generic organ structure (S_O):
Further refinement of F_N and B_N leads to S_O which is derived from a vision of a generic model inspired by Bond graph theory (Figure 4). Several Bond graph structures can be created, as the solution is not unique and also with the use of computer tools which allows for automatic mapping with F_N. For this case study, one bond graph structure organ in the form of separate functions is as shown in Figure 11.

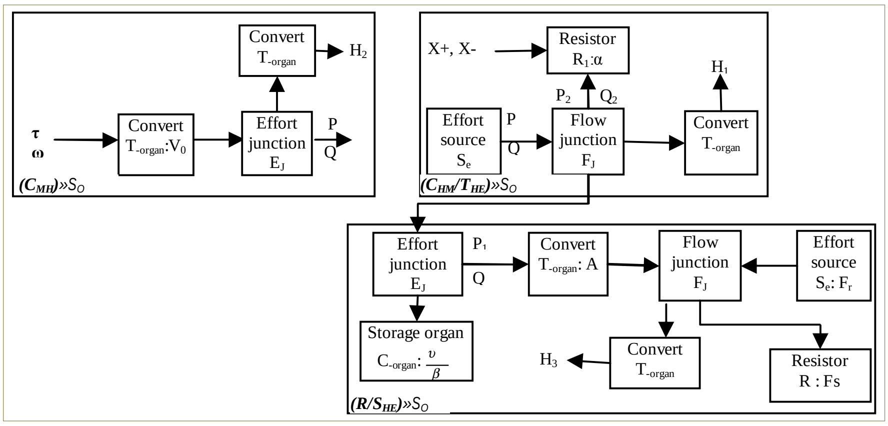

Figure 11. *Generic organ structure with Bond graph model*

A list of generic attributes based on a generic classification of variables (Coatanéa, 2005) derived from Bond graph and the taxonomy of Hirtz et al. (2002) emerges and is summarized in

Table **1**.

Table 1. *List of attributes from organ structure*

Function	Attributes names	Units	Quantities
Regulate and Separate	Thermal energy (H_1)	J	ML^2T^{-2}
	Displacement (X)	m	L
	Pressure lose (P_2)	Pa	$ML^{-1}T^{-2}$
Convert H_E to M_E	Volume/Bulk modulus (V/β)	m^3/Pa	$M^{-1}L^4T^2$
	Pressure (P_1)	Pa	$ML^{-1}T^{-2}$
	Surface (A)	m^3	L^3
	Force provided (F)	N	MLT^{-2}
	Thermal energy (H_3)	J	ML^2T^{-2}
	Reaction force (F_R)	N	MLT^{-2}
Convert M_E to H_E	Torque (τ)	Nm	ML^2T^{-2}
	Angular velocity (ω)	Rad/s	T^{-1}
	Volume (V_0)	m^3	L^3
	Thermal energy (H_2)	J	ML^2T^{-2}
	Pressure lose (P)	Pa	$ML^{-1}T^{-2}$
	Flow (Q)	M^3/s	L^3T^{-1}

-Step 6: Generic behaviour (B_O) modelling with dimensional analysis:

The list of attributes from step 5 is associated with the causality analysis of the Bond graph models, and this causality principle is used to define dependency and develop generic behaviour. It can be shown that F_N is completely determined by fifteen quantities as shown in equation [1].

$F_N = f(H_1, X, P_2, V/\beta, P_1, A, F, H_3, F_R, \tau, \omega, V_0, H_2, P, Q)$ [1]

Inspection of the above shows that the five quantities F_S, H_1, V/β, ω and V_0 for example, consist of a complete dimensionally independent subset of the fifteen variables. The dimension of any one of these five cannot be made up of the dimensions of the others. Manipulation of these variables by creating clusters using Butterfield (2001) algorithm, and using the product theorem and the partial derivation model developed by Bashkar and Nigam (1990) helps to derive new elements describing the behaviour of the generic organ structure (equations [2-11]) (Coatanéa, 2005).

$$\Pi_1 = P_2.Fs..H_1.\left(\frac{V}{\beta}\right)^{-1} \quad [2]$$

$$\Pi_2 = P_1.Fs..H_1.\left(\frac{V}{\beta}\right)^{-1} \quad [3]$$

$$\Pi_3 = F_R.Fs \quad [4]$$

$$\Pi_4 = \tau.H_1 \quad [5]$$

$$\Pi_5 = H_2.H_1^{-1} \quad [6]$$

$$\Pi_6 = P.Fs..H_1.\left(\frac{V}{\beta}\right)^{-1} \quad [7]$$

$$\Pi_7 = Q.\omega.V_0 \quad [8]$$

$$\Pi_8 = A..\left(\frac{V}{\beta}\right)^{-1}.H_1 \quad [9]$$

$$\Pi_9 = H_3.H_1^{-1} \quad [10]$$

$$\Pi_{10} = X.Fs.H_1^{-1} \quad [11]$$

Figure 12 shows the extended model of the behaviour of the organ structure, which is compiled by combining Petri nets and π-numbers. Due to the application of Petri nets, the rules of this modeling language have to be followed when simulating the system with this model.

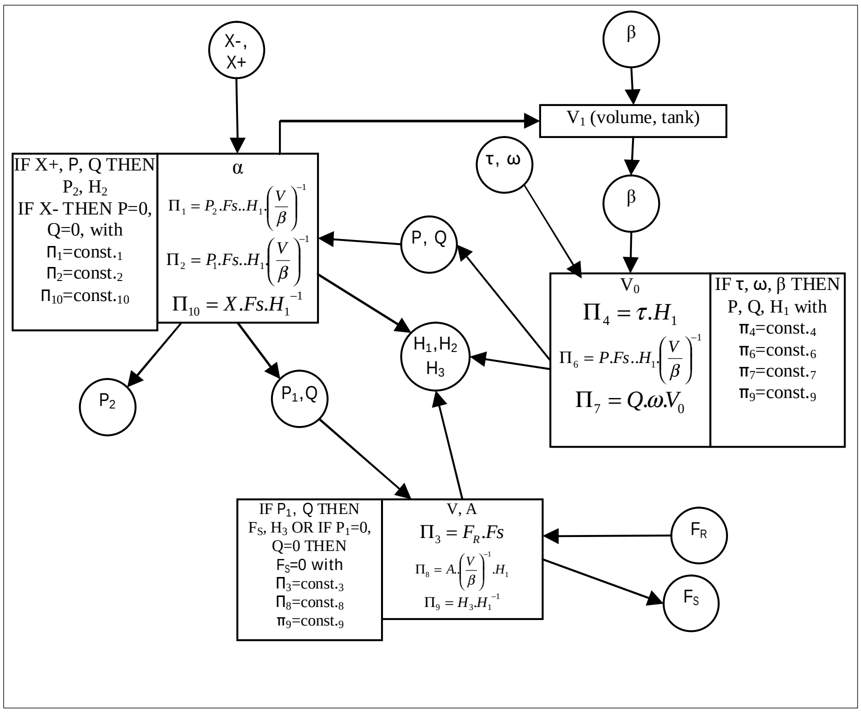

Figure 12. *Generic organ behaviour with Petri-net and Π-numbers*

The formal dimensional analysis approach that lies behind this model helps in transferring it into some appropriate simulation software and thus enables the automation of modelling-simulation process. It also makes possible to analyze failures and the propagation modes at a very abstract level of design. The comparison between the expected behaviour and the generic behaviour is a subject for future analysis and is therefore not discussed in this article.

-Step 7: transformation of function structure (F_S) to component structure (F_C) based on S_O and B_O with configuration flow graph (CFG)
The next level of abstraction in the conceptual design phase is finding working principles for the function structure. A working principle must reflect the physical effect needed for fulfilment of a given function and also its geometrical and material characteristics or form design (Pahl *et al.,* 2007). The physical effect has been analyzed in steps 4 and 6 as B_N which is transformed to derive S_O and B_O. These are further transformed to obtain F_C using CFG by mapping the desired functionality into the component configuration domain (Kurtoglu et al., 2008).

The component types in a CFG can be thought of as generic abstractions of common component concepts (for instance, valve, tank, junction, dc motor, battery). The CFG is a specific implementation of the topology or the configuration of a system and replaces the conventional method of presenting the nature and form of function carriers by way of freehand sketches. CFG is implemented together with *conventional methods* of literature search and analysis of existing designs, *intuitive methods* like brainstorming, and *discursive methods* which is systematic search with classification and combination schemes (TRIZ, morphological analysis) to generate S_C. An example of four concepts from the result of the analysis captured with CFG through mapping with F_S and based on F_O and B_O is shown in Figure 13.

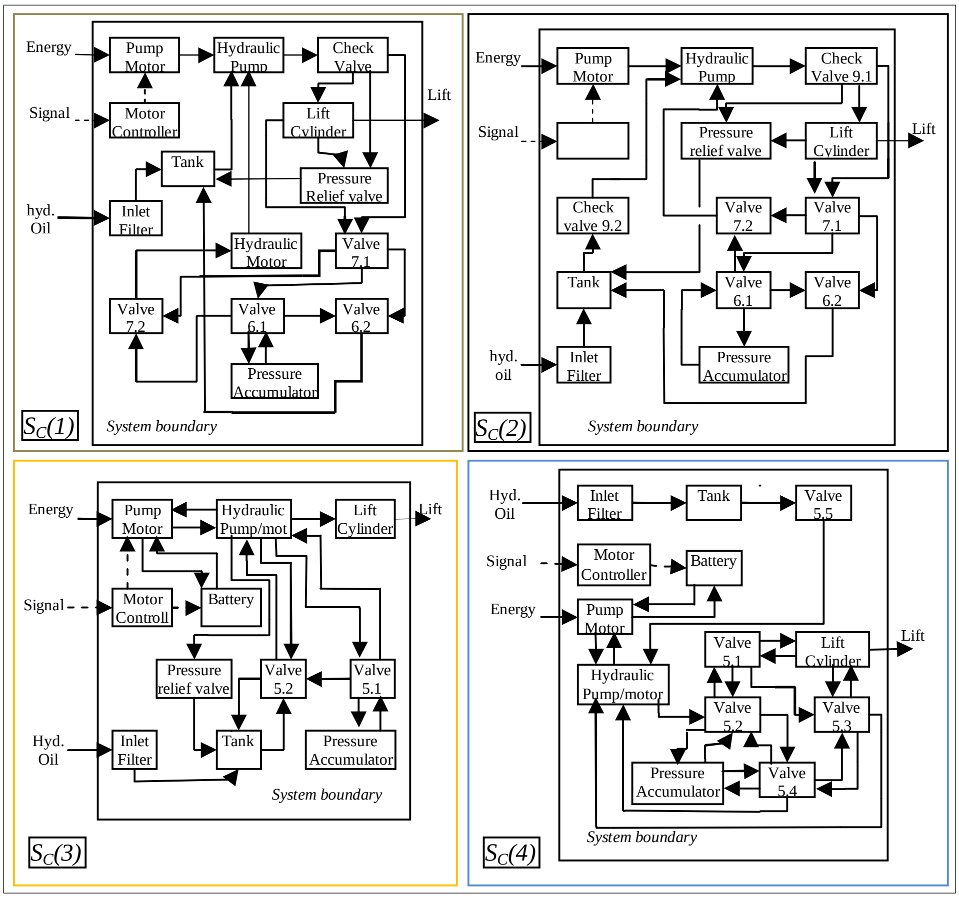

Figure 13. *Component structures with configuration flow graph*

5. Conclusion

The goal of the research presented in this paper is to establish a formal design synthesis which already at the early phase of design enables the functional and failure analysis of the designed system. The systematic methodology that lies behind the proposed method allows the use of computers throughout the design process.

This in turn allows the design teams to have at their disposal an integrated design tool in addition to the intuitive methods, creativity and experience of the designers.

The proposed formal early design synthesis model is formulated by an integration of function-based design process and function-behaviour-structure. The model seeks to produce innovative solutions guided by theories and principles. Based on the formalization the design process can be coded and thus automated with the help of computers and simulation programmes.

In this paper the theory behind this formal design synthesis is presented and implemented in a case study. The emphasis of this work is not just to generate a design model framework, but to formalize the design process.

The case study, a work system of a mobile working machine, demonstrates the unique capabilities of the proposed framework. These include a systematic way of idea exteriorization and concept generation, the realization of smooth transition from needs to comprehensive initial modelling, integration in a common model processes and artefact, and engagement of computer systems in conceptualization on a higher level of semantics and synergism.

There are also several areas where the present model framework can be improved. For instance, with the use of function models, heuristic modularity as the underlying modelling scheme for system representation introduces inherent limitations.

Areas identified for future work include developing all the ontology layers and the modelling approach through computer effort with the intention to obtain an automatic early design process. Another area includes investigating other critical phases of the model, namely the task clarification phase, principle solution phase and thorough analysis of the working principle phase. The long-term aim is to integrate the developed model framework into SysML modeling language.

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