Abstract

Nowadays, the ever-increasing complexity of systems with highly interconnected activities makes it difficult to manage the uncertainty that is inherent to engineering design processes. This leads to the necessity of structured models supporting process modeling. However, what is still missing is a general theoretical model that may potentially be able to provide multi-perspective knowledge on design processes, i.e., the possibility of supporting model interpretation from different aspects. In this paper, we propose an “integrated theoretical framework” with the aim to provide management with detailed knowledge on a given design process. The approach is composed of two phases that are implemented within four steps. First, an “inspiration triangle” of product lifecycle layers, areas of relevant factors with dependencies, and essentiality-effect matrix provides a basis on which an “integrated reference model” can be established. The framework is exemplified for a hypothetical case of an activity-based design process, with a focus on the role of uncertainty on dependencies. Finally, some managerial insights for process modeling are given.

Keywords: Structured model; Integrated theoretical framework; Engineering design; Design process management

1. Introduction

During the last decades, engineering design (ED) has been identified as a separate field within the spectrum of engineering disciplines. However, despite 50 years of ED research, it is not so easy to find a common view on design research, despite some notable attempts. In a chronological typology of design research, Wallace and Blessing [1] categorized design research contributions into three overlapping phases: experiential, intellectual, and experimental. As the result, it is claimed that “there is no common view as to what design research attempts to investigate, what its aims are and how it should be investigated. Many different methods are applied, many different aims pursued and many different aspects investigated” [2].

When focusing on the management of Design Processes (DP), the effectiveness of research is also quite subject to controversy. From one side, the existence of different views is termed as a strength [3], while on the other side, there are advocates of greater integration between research results. For instance, Cantamessa [4] believes that “while variety has the potential of delivering value, this is not a certainty. It left to itself, there is a risk that research may end up in a set of unconnected streams and in a sort of methodological anarchy where anyone can come along and claim the scientific validity of his work”.

To our belief, one possible reason behind this situation is the lack of an overarching multi-dimensional framework, rich in its capability of integrating knowledge on the DP, and which can support the understanding of a broad range of actors involved in the DP. From one side, the level of abstraction in theoretical models is a parameter that can affect their application. A well-founded model, aimed at a single purpose, confines its application to a limited audience (e.g. [5, 6]). Conversely, a model with high level of abstraction,
though it has the potential of being applied to a variety of disciplines, cannot support stakeholders with detailed information in process management. This, in turn, can limit the application of the model (e.g. [2, 7]). Ideally, any audience with a specific level of knowledge and viewpoint on the DP should be able to provide a contribution, and be supported by relevant detailed information. On the other side, it should be possible to integrate this specific perspective into a wider framework, allowing the management of dependencies between different levels and perspectives. Based on this reflection, we propose a multi-perspective integrated framework that focuses on the interactions between functional elements across different perspectives relevant to the DP. The main objective is to provide a theoretical support to facilitate knowledge acquisition, by taking multiple types of process attributes into account in an integrated form.

Methodologically, we propose a multi-perspective integrated framework, through a two-phase procedure, consisting of an “inspiration triangle” and an “integrated reference model” (IRM). The whole framework can be developed on four steps of initialization (initializing inputs), customization (constructing the triangle), monitoring (structuring the IRM), and validation (simulation, analysis and improvement). Hence, the next section 2 describes the proposed framework in detail. In section 3, a discussion on a hypothetical case focusing on information flows is provided. Conclusions are given in section 4.

2. Integrated theoretical framework for managing DPs

2.1. Fundamentals and methodology

With regard to literature, theoretical models are normally used as a baseline for developing tools for DP improvement. This follows a systematic way of thinking about models and their implementations, based on the idea that every model can be viewed as a collection of distinct elements. In [8] Gass and Harris categorized these elements into five types: primitive entity, compound entity, attribute, function and test elements. Due to their significance in capturing DPs, structured models can be quite fruitful or quite deceptive, depending on the magnitude and correctness of information extracted from the model. Ulrich and Eppinger [9] enumerated three justifications related to the helpfulness of structured models: making decision process explicit, acting as a checklist, and being largely self-documenting.

As mentioned in section 1, our contribution is to provide a theoretical support for DP management with respect to level of detail and information dependencies among elements. To clarify the level of detail used in structuring the framework, we follow the classification of Geoffrion [10], in which he introduced three levels of detail for structured modelling languages as, elemental, generic, and modular structure. Hence, we have selected the elemental level in order to cover more detailed characteristics of the DP architecture. For the latter, a graphical dependency representation is selected to capture information flows, as in a cause-and-effect diagram [11], due to its flexible, simple and easy to understand structure, especially in the case of capturing multiple flows in a large-scale system. Graphical diagramming also has the benefit of mapping multiple views of the entire system that alternatively can capture interdependencies between different organizational levels.

Methodologically, the proposed framework is composed of four steps, i.e., initialization, customization, monitoring, and validation (Figure 1). Following the classification of elements by Gass and Harris [8], types of elements should at first be identified by decomposing the DP problem hierarchically. Input information (step 1) is normally accessible by using typical WBS (Work Breakdown Structure) and BOM (Bill Of Material) documents. Moreover, during the first step, various types of dependencies between elements, and the essentiality-effect matrix (described later) should be initialized. In practice, there may be other exogenous elements (e.g. technology uncertainty) that can cast external influences on the DP. This kind of elements can also be embedded in the model, due to their effect on process behaviour. Customization can be carried out by assigning elements to their corresponding organizational layers (i.e., managerial, organizational and individual, that will be discussed later in sub-section 2.2.), identifying product/process orientation of the elements, identifying direct/indirect and positive/negative dependencies, and identifying the essentiality-effect matrix.

Monitoring refers to structuring the Integrated Reference Model (IRM) in the second phase. Here, modifications are allowed (both by inserting new exogenous elements into the system, or modifying dependencies between elements) and would be applied as a feedback to the original schemes. As the IRM is monitored, validation allows to running as finalizing the second phase. As the IRM is structurally established on a cause-and-effect diagram, it is potentially possible to support this phase by using System Dynamics. Information flows, including feed-forward and feedback loops, are of crucial importance in this step. Figure 1 indicates the overall procedure with its sequential steps. During the next section, the “Inspiration Triangle” of the first phase will be described.

2.2. Inspiration Triangle

a) Product life-cycle layers of DP

Functionality of DP management can be tied up to different organizational levels, pertaining to the entire product lifecycle. Blessing [1] emphasizes that design requires not only knowledge of stakeholder goals and of the product, but also of its life cycle. In an empirical analysis Cantamessa et al. [12] highlighted how product lifecycle management (PLM) should be studied at the three levels of strategy, organizational, and individual. Following this line of thought, this paper too will follow three organizational (or PLM) levels (i.e., managerial, organizational process, and individual). So, all functional elements that are collected in the initialization step will be categorized into their corresponding PLM layer. The term “functional” above refers to all kinds of primitive and compound elements (following the classification by [8]), and each of them can be originated either from inside the DP (endogenous) or from the outside (exogenous). We mean compound wherever a functional element is composed of other functional elements. Thus, the players of proposed
framework would be primitive and compound elements based upon which the model is established, while function and attributes (Fig. 1) are applied to categorizing these elements.

Structurally, the PLM layer diagram constructs during customization step, where input primitive and compound elements categorize into their corresponding PLM layer. The scheme (PLM layers) consists of three overlapped ovals with centrality of the problem (DP), or sub-problem (compound element) which is presented in Figure 2 in an integrated form. However, the scheme can be constructed for any compound element, depending on the complexity of the DP. Since the procedure is iterative, improvements on the positions of elements are allowed during the monitoring and validation steps (phase 2). Through the PLM layers diagram, it is of our interest to get some insights on finding critical elements within each PLM level. Maintainability and simple tracing mechanism on an element (to its origination or to the corresponding PLM level) can be considered two major strengths of this diagram. The diagram is depicted in Figure 2, for the sample hypothetical case.

b) Areas of relevant DP elements with dependencies

Through the areas of relevant diagram, we aim to categorize the primitive and compound elements based on their direct and indirect dependencies. The latter is, to some extent, comparable to what Blessing developed as the “areas of relevance and contribution” (ARC) diagram [2] with some modifications, specifically in terms of representing dependencies. Normally, there can be different ways to classify functional elements, i.e., based on their relevance and based on their hierarchical level in the DP. We suggest the combination of relevance with hierarchical level. This means that, based on the hierarchy of DP, the main problem (e.g. DP management) connects to its major relevant elements, while each of these elements by itself can be branched out to other relevant elements. The procedure continues by going into more detailed elements of the DP. In terms of dependencies, there are logically direct dependencies between the elements within the same branch, while there can be indirect dependencies for the elements among branches (even in the same hierarchical level). This is indicated in Figure 2, as an example with shortened number of dependencies. In the case of complex DPs, this graphical representation helps capturing the direct and indirect dependencies between levels, since the majority of the elements originate from more than one cause.

Like the PLM layers diagram, this scheme is developed during the customization step, with the possibility of further improvement and refinement during the monitoring and validation steps. Inputs required for this diagram are primitive and compound elements, dependency functions with clarification on direct/indirect types, and orientation attributes (product- or process-related). Product/process orientation in this diagram can be helpful to clarify the relevance of functional elements. Graphically, the diagram is consist of boxes and lines (Fig. 2), where boxes are indicators of (primitive and compound) elements, filled lines are direct dependencies, and dotted lines are indirect ones. In order to enrich the diagram, it is possible to use arrows instead of lines, to demonstrate the direction of dependencies. Simple structure, maintainability, ease of tracking an element to its origination and its dependency network can be enumerated as some advantages of this diagram.

c) Essentiality-effect matrix

Identification of critical factors has been the concern of a variety of research efforts in DP modelling (e.g. see [13, 14]). The latter is of significant importance, particularly in the sense of managing DPs. Referring to previous sub-sections (a,b), the simple tracking mechanism proposed was claimed to be a major advantage of such framework. Hence, it is crucially important to be able to find essential elements and track their effects. So this part can complement the previous parts, by presenting a matrix-based tool to identify essentiality and effect of functional elements. The primitive and compound elements are categorized based on their types of essentiality and also their effects. We consider two types of essentiality for elements (essential and useful), and similarly two types of their effects (incentive or positive effect, and disincentive or negative effect). Figure 2 depicts this matrix. Nonetheless, since inputs of both attributes (essentiality and effect) are provided subjectively through a data collection
Fig. 2. Integrated two-phase framework; triangle and IRM
methods (e.g. interviews, questionnaires, document analysis), outputs can be accordingly quite subjective. Of notable importance is that, while the essentiality-effect matrix provides a support to identify critical elements, it is also valuable to investigate the essentiality of an element with respect to its dependencies with other elements, especially when they come from different PLM layers. This can consequently support managers with insights on identifying critical elements, while it is only possible through an integrated form.

To summarize, the diagrams generated during the first phase allow the collection of a broad amount of tacit knowledge on DP management from different perspectives, while providing a basis for establishing the second phase, in the IRM.

### 2.3. Integrated Reference Model

The foundation of the proposed IRM in this paper is a cause-and-effect diagram that is mainly used in Systems Dynamics approach [11]. This cause-and-effect diagram is then supplemented with attributes (orientation, essentiality, effect) to provide more detailed knowledge in an integrated form. Structurally, elements of the IRM are primitive and compound elements which, as mentioned before, they can be endogenous or exogenous. These elements are linked together through a range of interdependencies depicted as arrows (Fig. 2). To demonstrate the positive or negative type of dependencies in IRM, positive or negative symbols are used. Based upon the information from the first phase (steps 1, 2), including functions (dependencies) and attributes (product/process orientation, essentiality, effect), IRM in second phase (step 3) can be constructed for a set of functional elements.

Positioning of the elements directly depends on their PLM level and also their product/process orientation attribute. In our case, we organized the elements horizontally based on three PLM levels, and vertically based on their orientation. Moreover, coloured notations are used in terms of essentiality and effect attributes, where a green colour determines essential elements with incentive effect, and the red colour essential elements with disincentive effects. To recall, incentive and disincentive effects respectively determine the positive and negative effects of elements. For instance, for a given element as “process risk” in Figure 2, its orientation is process-related, while it is well-suited in organizational process layer of PLM. As achievement, the goal is to get insights on tracking sinks (successors), sources (predecessors), dependencies, product-process orientation, and corresponding audience (PLM level). Gaining this sort of detailed information can be facilitated by means of a graphical representation. Hence, three major strengths on the proposed model would be the possibility of monitoring large-scale complex systems, of facilitating detailed knowledge capture, and of making status tracking easy and at a glance. The next section is dedicated to validate the information flows (feed-forwards and feedbacks) on an example of activity-based DP.

### 3. Hypothetical case and discussion

Referring to the literature, reference models are usually used as a theoretical support on the existing situation of DPs [2]. Their relevance and accuracy can therefore directly affect further steps in process improvement. Thus, step 4 on the second phase of the proposed framework consists in taking the validation and improvement into account, given a hypothetical case of an activity-based DP as example. In literature on DP modelling, dynamic task models (e.g. Signposting [13], ATP [15]) are considered to be quite efficient tools, due to their dynamic nature in capturing uncertainty and dependencies. Based on the aim of paper, by highlighting dependencies between functional elements, we recognized that the basic characteristics of Extended Signposting (ES) [13] are well-fitted to our aim. Hence, these major features are imported into the model as primitive and compound elements, from a rather abstract level. The reason on the abstraction of hypothetical case is twofold: first, compatibility to a variety of modelling approaches in literature, and second to facilitate understanding of the paper contribution per se.

By looking inside the IRM (Figure 2), the iterative nature of DPs is quite visible, thanks to the flows of dependencies from down to up, and to the feedbacks that normally start from the “customer satisfaction” element. From a micro-level, tracing essential elements can be helpful to give detailed information. For instance, the element “knowledge of actors” can affect in four ways “process uncertainty” element, as Figure 3 indicates three routes with their positive/negative type of dependency. This case reveals that, in the context of complex systems, there can multiple types of direct and indirect dependencies between functional elements. Other similar cases are existed within IRM, like “Degree of concurrency” and “Completion time of DP”. This is also of interest for example to understand how negotiation between actors is occurred (left side in IRM), in which PLM level (organizational process), and what they affect (process complexity and uncertainty). Similar investigations are simply possible for other kinds of attributes (e.g. essentiality). Updatability here is the strong feature, since new information (elements, dependencies) can be readily applied into IRM.

![Fig. 3. An example for direct/indirect dependencies between elements](image)

From a macro-level, the overall behaviour of IRM is concerned with the relevance and accuracy of dependencies. As mentioned before in section 2.1., an advantage to the proposed model is that can satisfy the requirements of the Systems Dynamics (SD) approach and can therefore be supported by a SD simulation tool. In this way, the model was implemented in Vensim@ to validate dependencies. The result indicates six feedback loops with the length from six to
nine elements (which means no error was made in model construction). As expected before, elements such as “process uncertainty, completion time, design structure improvement, and knowledge on process” are embedded in all of them, and so require specific attention in our case. However, in order for further investigation to find critical elements, it is also possible to assign a specific weight to each pre-determined essential element. Doing this, sensitivity analysis of process behaviour can allow a deeper understanding on criticality of elements, which however is out of the scope of this paper.

Nonetheless, evidences from the previous discussion confirmed the strengths of proposed framework, which were partially mentioned in section 2. Multi-aspect graphical representation, as the main contribution of this paper, provides detailed knowledge on the problem, due to its flexibility and powerful tracking mechanism. In presence of other attributes like PLM levels, product/process orientation, and essentiality-effect matrix, the framework can reflect multi-perspective information in support of management; however, there should be caution on level of abstraction to make a balance between rigor and flexibility.

4. Conclusive remarks

Inherent uncertainty in today’s complex systems makes it important to advance research in DP modelling. This also requires to advance structured theoretical models while, up to date, there is still missing an overarching theoretical model that potentially may be able to provide multi-perspective knowledge on DPs. Hence, in this paper, we aimed to provide an informative support for DP management, by proposing a two-phase integrated theoretical framework through a four-step procedure. During the first phase, input information constructed the inspiration triangle, based on which an IRM presented in second phase. Operators of the proposed framework were functional elements (primitive, compound), functions (dependencies), and a sort of attributes (PLM layers, product/process orientation, essentiality, effect). We were mainly intended to present a structured tool to identifying critical elements as well as some insights on their dependencies. So major characteristics of a hypothetical ES approach distinguished and imported to our framework as a framework? In: Int Conf on Eng Design (ICE'D03). 19-21 August 2003, Stockholm; 2003.

[13] O'Donovan BD, Clarkson PJ, Eckert MC. Signposting: modeling uncertainty in design processes. In: Proc of the 14th Int Conf on Eng Design (ICE'D03). 19-21 August 2003, Stockholm; 2003.

[14] Browning TR, Fricke E, Negele H. Key concepts in modeling product development processes. Sys Eng 2006;9(2):104-128.

[15] Levardy V, Browning TR. An adaptive process model to support product development project management. IEEE Trans Eng Manag 2009;56(4):600-620.

[16] Smith RP, Morrow JA. Product development process modeling. Design Studies 1999; 20(3):237-261.

References

[1] Wallace KM, Blessing LTM. Observations on some German contributions to engineering design. In memory of Professor Wolfgang Beitz. Res Eng Design 2000;12: 2-7.

[2] Blessing LTM, Chakrabarti A. DRM: A design research methodology.