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MODELLING THE DESIGN PARAMETERS DYNAMICS WITH PETRI NETS

Juranic, Jasmin (1); Pavkovic, Neven (1); Naumann, Thomas (2); Marjanovic, Dorian (1)
1: University of Zagreb, Croatia; 2: Daimler AG, Germany

Abstract

The aim of the presented research is to develop methods and tools which would enable consistent dynamic updating and propagation of updated design information in teamwork in a manner that will not generate additional tasks for designers. The research has been focused on management of design parameters, especially to issues that occur in collaborative teamwork when several designers work on a group of coupled parameters. An example of a complex assembly design process has been analysed to demonstrate the suitability of Coloured Petri nets for modelling dynamics of design parameters. Based on initial results authors believe that it is worthwhile to continue with the approach where repetitive patterns of communication situations and parts of the design process will be extracted and modelled with Coloured Petri nets in form of generic templates. The implementation of the proposed model should be able to suggest and approve the automatic launch of small parts (sequences) of the process with the aim of gradual automatization of recognised information processing and information transferring activities.

Keywords: Coloured Petri nets, Collaborative design, Engineering parameters, Communication, Design management

Contact:
Jasmin Juranic
University of Zagreb
Chair of Design
Croatia
jasmin.juranic@fsb.hr

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1 INTRODUCTION AND PROBLEM STATEMENT

Today, a new product development process is mostly a teamwork including engineers and many other professionals. They are very often geographically dislocated hence development processes are conducted in multinational and multidisciplinary environments. In such conditions, coordination and communication between stakeholders become complex problems of primary interest (Yang et al., 2015). Dynamic market competition increases the number of product variants and product components, initiates the usage of advanced manufacturing technologies and reduces the time from an idea to the market ready products (Kahn et al., 2012). A product complexity is manifested through its function, technology, shape and integration with other systems of lower or higher complexity level. The Complexity of a product development process can be seen in a number of activities, number and characteristics of stakeholders, characteristics of teams and organisations and their interrelations (Browning, 2016; Wynn et al., 2012). Product lifecycle management (PLM) is a collection of practices, methods, and tools that help organizations to cope with the increased complexity of today's engineering activities. According to (Karniel and Reich, 2011a) there are two fundamental enablers in PLM: data management and process management and various services built upon them: visualization, CAD interoperability, system engineering, collaboration and interoperability with other organisational business systems. While extending and improving the capabilities of PLM systems in this way, one fundamental question remains silent (Karniel and Reich, 2011a): **are we sure that the various services or even the fundamental aspect of PLM - process management - is using updated product information in its operation?**
Recent research in automotive industry (Königs, 2014; Toepfer and Naumann, 2016) confirms that PLM systems in the industry do not sufficiently address this question; they do not adequately support communication and exchange of information and knowledge between team members, especially in the case of low granularity of engineering information such as design parameters.
In the context of this research, we will define an engineering parameter according to Toepfer and Naumann (2017): *An Engineering Parameter represents any characteristic of quality and relation which can specifically be described by a quantity. It thereby explicitly carries the name of the describing characteristic and a quantity (numerical value and optionally a unit).* This definition is based on Ropohl (2009) which considers parameters as quantifiable characteristics that can describe all quantifiable and measurable entities of a system, as well as the system itself.
The aim of the presented research is to analyse the possibilities for improvements of design parameter management in teamwork development of complex products. The proposed approach partially builds on the research of methods and tools for supporting team communication in the dynamic and iterative process of defining values for a set of coupled design parameters that have begun with papers (Clarkson and Hamilton, 2000; Eckert et al., 2001; Flanagan et al., 2003). Flanagan and others (Flanagan et al., 2003) claim that individuals often have very little idea how their own tasks fit into the context of the whole product despite being experts in their own field and understanding the tasks of the people they work with frequently. The issues exist both in communication as well as in the visualisation of flow and status of a project; team members may have little idea where information is coming from or going to and who is using it in the wider product context. All these papers emphasize the need for the research and development of efficient methods and tools for managing the dynamics of design parameters in the circumstances of complex product development teamwork which include many coupled (interrelated) parameters. Some aspects of coupled parameters issues are covered by Design Structure Matrix (Browning, 2016; Lindemann et al., 2009) and related methods, but only on the static level and by no means on the dynamic level (Karniel and Reich, 2011b, 2013).
The ability to access and share consistently updated information instantly does not guarantee its proper use (Karniel and Reich, 2011a); yet, having a seamless integration of the changing product information and its propagation to dynamic process planning and execution is critical to coping with the product development process management challenges (Karniel and Reich, 2011b; Wynn, Caldwell and Clarkson, 2014). Authors claim that process management that is executed through embedded workflow tools is incapable of integrating updated product information into dynamic run-time operation. Various aspects of this problem were addressed for static scheme processes (Amigo et al., 2013), but according to (Karniel and Reich, 2011a, 2011b, 2013) no method was found to address the demands of dynamically evolving schemes of product development processes.

Presented research is an ongoing cooperation with research centre of Daimler AG and is focused to issues of parameter management dynamics in the process of developing vehicle architecture (Toepfer and Naumann, 2016). Based on initial studies, further research directions were proposed where it is assumed that the usage of Petri nets (Petri, 1962) and its extensions and variations will provide possibilities to formalize, visualize and simulate the dynamics of parameter management while focusing on smaller sequences of a development process.

The development of high-level Petri nets removed some of their initial drawbacks and nowadays they are recognised as one of the most adequate and sound languages for description and analysis of synchronisation, communication and resource sharing between concurrent processes (Jensen and Kristensen, 2009). There are numerous successful industrial applications in modelling workflows (Van der Aalst et al., 2013) and also the proposals to combine Petri nets with DSM (Karniel and Reich, 2011a). Coloured Petri Nets (CP-nets or CPNs) is a discrete-event modelling language combining the capabilities of Petri nets with the capabilities of a high-level programming language (Jensen and Kristensen, 2009). Modelling complex processes in terms of CPNs is a nontrivial task, but there are recurring modelling problems that can be solved by applying design patterns (Van der Aalst et al., 2013). The idea to provide patterns for modelling in terms of CPNs was first proposed in (Mulyar and van der Aalst, 2005a, 2005b). Based on expert opinions and an analysis of large collections of CPNs (taken from papers and Web pages), 34 patterns were identified. In (Van der Aalst et al., 2013) each pattern is described using a standard format including elements such as pattern name, intent, motivation, problem description, solution, implementation considerations, examples, and related patterns.

The presented research aims to apply a similar approach where several complex product development processes would be analysed to extract repetitive patterns of communication situations and process sequences. Extracted patterns would then be generalised and formalised aiming to be modelled with CPNs as templates for partial design parameter management process automatization. Researchers in Daimler AG (Toepfer and Naumann, 2016) are developing an approach where sets of closely related parameters from a vehicle module or sub-assembly are being isolated and grouped in order to focus design team communication on a smaller set of existing parameters. However, this approach does not completely resolve all previously discussed issues, because many of the parameters would exist in several parameter groups. It should be taken into account that the design parameters are used and processed in several different information systems (CAD, PDM, ERP, CRM) - consequently, they are often used in several different contexts by different stakeholders. This information processing activities are mainly the responsibilities of involved design engineers which unfortunately burden them with unnecessary routine (instead of creative) tasks. The ultimate goal of proposed Petri nets application should be to partially automatize suitable sequences or patterns of such information processing activities.

Based on the presented approach and discussed problem statements, this paper aims to answer the following research questions:

1. How the complexity of a system being designed impacts proposed management of design parameters and practical usage issues?
2. What are the crucial situations and patterns of situations that may arise in dynamics of design parameters network?
3. What are limitations on Petri Nets in suggested approach and how will those limitations affect everyday usage?

The third question will be of primary interest in this paper while the first and second will be used to guide and shape the presented case study and future work.

2 PETRI NETS AND COLOURED PETRI NETS

Petri net is a mathematical representation for modelling discrete event dynamic systems. Petri net is also a graphical representation of the system and it depicts the structure of the system using bipartite directed graph. The graph consists of nodes and directed arcs. Nodes are places represented by circles and transitions represented by rectangles. The arcs could be directed from a place to a transition or vice versa. Figure 1a shows a basic example of Petri net marked with tokens (black dots) in the initial state. A transition in a Petri net may fire if it has at least one token in each input place. After firing, the transition uses one token from each of its input places and deposits tokens into each of its output places. This situation is shown in Figure 1b. In “classical” Petri net we could consider a transition as design

activity and a place as a design parameter state. To be able to model an execution of a specific design activity, all required design parameters have to be instantiated.
Petri nets were introduced in a Ph.D. dissertation of Carl Petri in 1962. However, attempts to use Petri nets in practice revealed two serious drawbacks (Jensen and Kristensen, 2009). First of all, there were no data concepts and hence the models often became excessively large, because all data manipulation had to be represented directly into the net structure (i.e., by means of places and transitions). Secondly, there were no hierarchy concepts, and thus it was not possible to build a large model via a set of separate sub models with well-defined interfaces. The development of high-level Petri nets removed these two serious problems (Jensen and Kristensen, 2009).

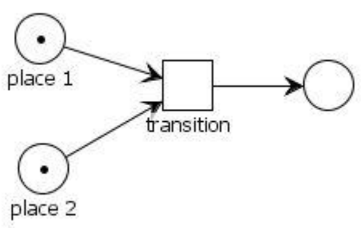

Figure 1a. Petri net before firing

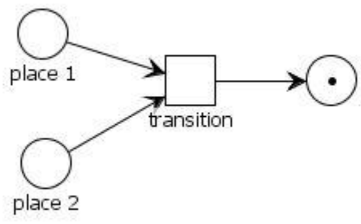

Figure1b. Petri net after firing

Coloured Petri Nets (also called CP-nets or CPN) is the most well-known kind of high-level Petri nets. CP-nets incorporate both data structuring and hierarchical decomposition - without compromising the qualities of the original Petri nets. Tokens in a CPN carry a data value and have a timestamp. The data value, often referred to as colour, describes the properties of the object modelled by the token. The timestamp indicates the earliest time at which the token may be consumed. Transitions can assign a delay to produced tokens. This way waiting and service times can be modelled. A CPN may be hierarchical, i.e., transitions can be decomposed into sub processes. This way large models can be structured. CPN Tools is a toolset providing support for the modelling and analysis of CPNs (Jensen et al., 2007).

3 RELATED WORK

Many authors view design process as a sequence of transformations (transitions) of product attributes where design evolve from its initial state to a final state. An initial product description typically has only main design parameters defined, according to main requirements. The rest of parameters are being progressively instantiated and defined through an iterative process of transformations. Dynamics of such process in teamwork environment is very complex and could raise serious issues, increase lead time and expenses especially if coordination and communication about coupled (interrelated) parameters (which are shared and used by more team members) are not efficiently organized and supported by existing software tools. Although the research on these issues started about 25 years ago, in the meantime the complexity raised even faster, hence, the same issues are still present today and are also emphasized in the latest papers (Eckert and Clarkson, 2010; Amigo et al., 2013; Clarkson et al., 2014; Wynn et al., 2016).
In McMahon and Xianyi (1996), the authors have presented a method for the integration of multiple computing processes for a parametric design problem. The processes are regarded as performing transformations between model states where sequences of transformations and model states are modelled using Petri nets. A similar approach is proposed by Horváth et al., (2000) - the application of advanced Petri-net (APN) as a means for modelling design processes together with the decision patterns of designers. An APN is a bi-layer allocated architecture with linked, bipartitioned, directed, and attributed multi-graphs.
While reviewing the literature many examples of Petri nets for modelling team communication and process planning in combination with workflow systems may be found like e.g. (Karniel and Reich, 2013; Pla et al., 2014). Authors in various ways suggest development and usage of generic templates of communication processes. In this context, the very interesting paper is written by Khosravifar (2013) who proposes models (considered as templates) of negotiation, persuasion, defence locutions and seeking for information in the multiagent environment.

4 CASE STUDY OF CPN APPLICATION FOR MODELLING DESIGN PARAMETERS DYNAMICS

This section of the paper presents an example of a complex assembly design process to analyse and demonstrate the suitability of Coloured Petri nets for modelling dynamics of design parameters. The authors studied the example of multifunctional arm mounted on a firefighting robotic vehicle (Figure 2). The arm has several degrees of freedom and all joints are hydraulically powered. This assembly has two main functions. The first one is to enable a secure transfer of dangerous objects from a hazardous area. The second function is to extinguish the fire with included common water and foam cannon. This is a complex product which requires experts from different fields such as material science, machine elements, the strength of materials, manufacturing, hydraulics, fluid mechanics and heat transfer, electronics, electrics and software engineering to work together in order to make a market ready product which should be used in a hazardous environment. In this analysis, we will observe the example tasks of two designers which are responsible for the design of a gripper and for design and calculation of nozzle and water cannon assembly, respectively.

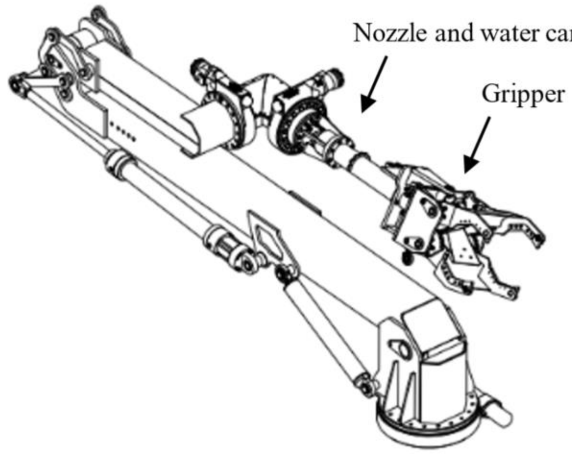

Figure 2. Multifunctional arm

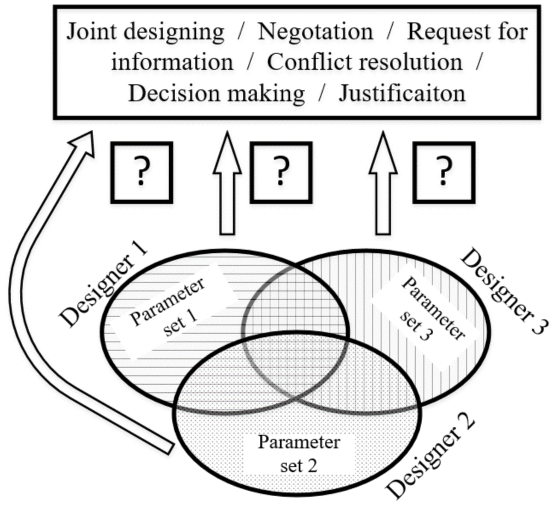

Figure 3. Resolving coupled parameters

Each designer is responsible for his set of parameters. In this step, we will consider only geometrical parameters. Since both designers work on assemblies having a component that are tightly coupled geometrically and functionally, they ought to collaborate. Not all parameters from one designer are important to others, hence, each designer should define a parameter subset from parameters which are important to him or may have the influence to others' parameters. A typical generalized situation of parameter sharing in the design process where several designers collaborate is shown in Figure 3.

As depicted in Figure 3 there exist parameters which belong or have a meaning only to one designer. One can change their value independently of others and those parameters probably would not arise any problem. Our point of interest are parameters which are interrelated or coupled. If Designer 1 (D1) designs the gripper and Designer 2 (D2) designs the water cannon they have common parameters. When D2 wants to calculate the thickness and diameter of the cannon tube one needs a value of gripper weight because the gripper is connected to the end of the tube. This information can be obtained from D1 but does D1 in that moment know the final value of gripper weight? D1 does not know what the weight is because in order to design the gripper one needs the value of the water cannon tube diameter from D2. Hence, these parameters are coupled. How to resolve this situation?

Those two parameters are not the only coupled parameters as can be seen in Figure 4. The figure shows relations between parameter sets from both assemblies, the gripper and the water cannon, respectively, in the form of parameter design structure matrix. This matrix does not include all parameters of manipulation arm assembly, just those that are important in presented analysis. It can be noticed that the gripper weight depends on several parameters from both assemblies. Also, the number of hydraulic hoses (hoses 1 quantity) from the gripper has an influence on the number of hoses on the water cannon (hoses 2 quantity) and several other parameters because the hoses are routed from the gripper over the water cannon and other assemblies towards the firefighting vehicle.

To get a better understanding of parameters, how they are changing during the design process and how the coupled parameters value are iteratively defined, initially the design process have been modelled by the “classical” Petri net model. Transitions have been defined as tasks in the design process and places as parameters. Each parameter has its own place. Tokens present states in a design process. It has been found that classical Petri nets have significant drawbacks - even for this relatively small example the final net was very big (approximately 200 nodes). Therefore we decided to use Coloured Petri nets.

		assembly 1 - gripper									assembly 2 - water cannon										
		cargo weight	cargo diameter	gripper length	cylinders quantity	hoses 1 quantity	hoses 1 diameter	hoses 1 position	flange 1 diameter	gripper weight	water flow	watercannon range	nozzle diameter	nozzle length	tube diameter	tube length	air intake area	watercannon weight	hoses 2 quantity	hoses 2 position	flange 2 diameter
assembly 1 - gripper	cargo weight																				
	cargo diameter																				
	gripper length	X	X																		
	cylinders quantity			X																	
	hoses 1 quantity				X																
	hoses 1 diameter			X	X																
	hoses 1 position				X	X	X														
	flange 1 diameter				X	X	X								X						X
	gripper weight			X	X	X	X	X	X						X	X					X
assembly 2 - water cannon	water flow																				
	watercannon range																				
	nozzle diameter										X	X									
	nozzle length										X	X	X								
	tube diameter									X	X	X	X	X							
	tube length										X	X	X	X	X						
	air intake area										X	X			X	X					
	watercannon weight									X					X	X					
	hoses 2 quantity					X															
	hoses 2 position					X	X	X													
	flange 2 diameter					X	X		X	X											

Figure 4. Design Structure Matrix of multifunctional arm parameters

An initial CPN model of described case study is presented in Figure 5 and it consists of three main parts indicated with dashed lines. One part is a gripper design process, another one is a design process for the water cannon and the third part is a (still not detailed) model of communication/collaboration process. Each of design process models has only two places – **requirements and parameters** (indicated by ellipses). One place is a requirements place and another is a parameters place. We use the requirements place to store parameters which are defined in specification and requirements list for specific assembly. Values of those parameters will not be changed by the designer, hence they are “read only” parameters and all arrows are directed opposite of the place. If requirement parameters are changed due to changes in specification, all activities which use parameters from requirements place should be executed again (recalculated or redesigned - depending on activity type). A parameters place contains all parameters whose value should be determined by the designer. At the beginning of a design process, a parameter place is an empty place which means that there are no parameters determined by a designer. As the process advances the parameters place fills with determined parameters. Parameters are determined in transitions or design activities represented by rectangles.

To be fired, a transition needs parameters to work with. Those parameters are in requirements place or parameters place depending on an activity. Some activities use parameters only from requirements place, the others only from parameters place and some from both places. When an activity is done (transition is fired), determined parameters are sent to parameters place. The list of parameters which are used in an activity is placed near to corresponding arrows. Arrows are directed from a transition or toward a transition, depending whether the transition needs parameters to fire or new value of parameters are the result of the transition.

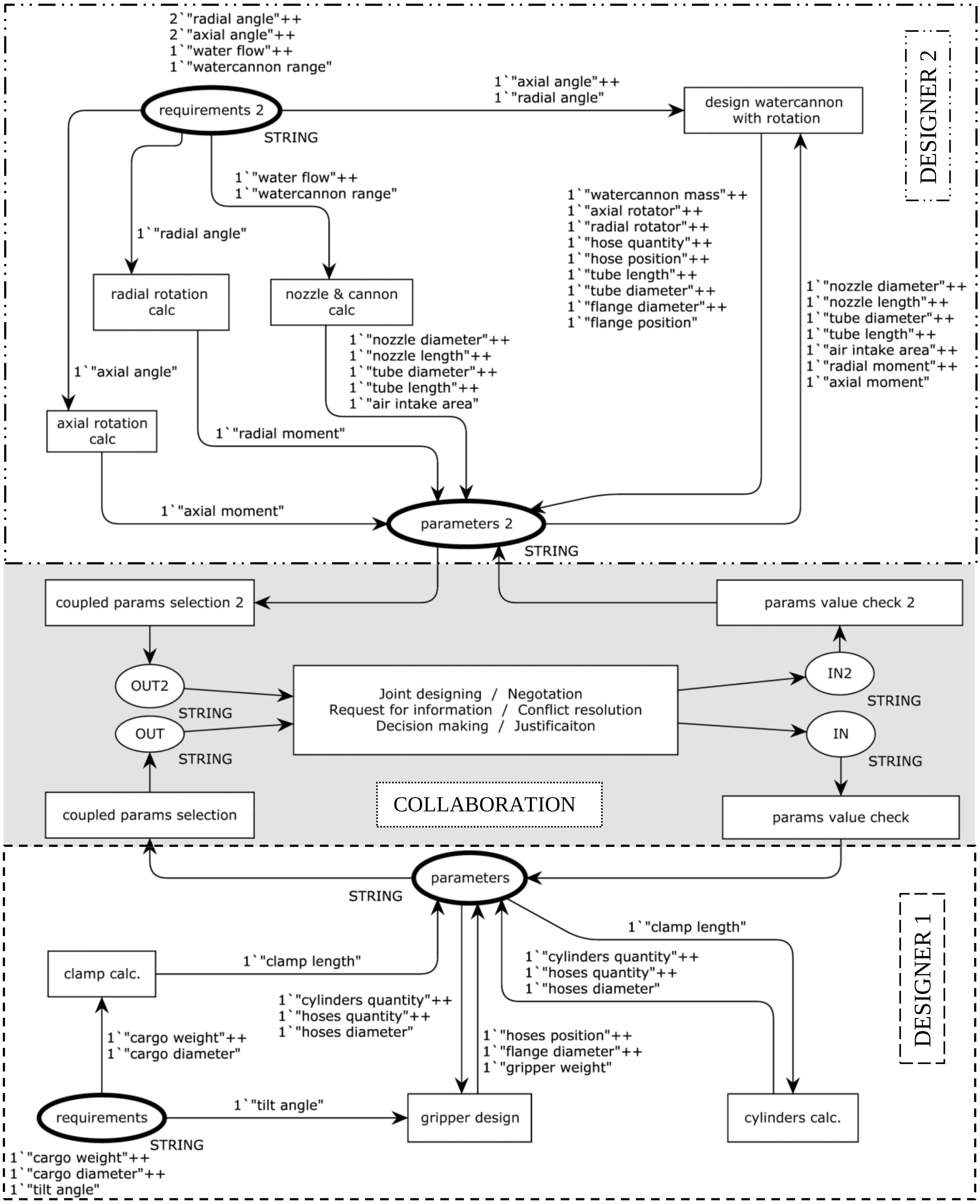

Figure 5. Initial CPN model of studied design process

As we point out before, each assembly is designed by the different designer. At some point in time, they ought to collaborate and to agree on the values of coupled parameters. This process is presented by the central part of the CPN model.

For any kind of collaboration the stakeholders should be known - in this model, these are designer 1 and designer 2. The subject of the collaboration should also be defined. A designer should decide what kind of collaboration he/she is willing to start and he/she should select which parameters are important for the collaboration. Parameters selection is performed in "coupled params selection" transition. Not all parameters are important for the collaboration. After the selection, parameters are placed in the place "OUT". After reviewing a request for collaboration, designer 2 should do the same thing. He/she should select his/her parameter set for the collaboration and those parameters will be placed in "OUT 2" place.

After the collaboration is finished, resulting values are forwarded to "IN" places. At that moment designers should review new values of parameters. If values are appropriate, those parameters are sent back in the parameters place.

It should be noted that this is an initial model - in this form the model is not executable since the central (collaboration) part is still not completely developed.

The collaboration could be conducted in a number of ways. Designers could design critical parts together or one designer could just ask for information on another's designer parameters. Sometimes they should negotiate about values if they work on critical parameters or even a conflict should be resolved. In certain situations, it would be sufficient to justify the values according to values of colleagues. These situations are listed in the central part on Figure 5. Such situations in research of design communication have been studied from many viewpoints. The future development of proposed model will mainly be based on classification and description of these situations given by (Eckert and Stacey, 2001) and the analysis of factors influencing communication given by (Maier et al, 2008). We expect that a combination of results of these two papers will give us a good theoretical background. The presented starting phase of the research has been focused to modelling "simpler" issues of design parameter management - where one designer is responsible for one set of parameters - like examples of gripper design and water cannon design. The next "more complex" step is to model the process of "resolving" values of coupled parameters. This task is not trivial if we want to consider all the issues at the lowest granularity levels of design parameter management, especially the need to consistently update parameters and to propagate updated values to all stakeholders in product development process.

Based on issues discussed in paper introduction and experience gathered while creating the presented case study example we believe that the next step should be to develop "generalised" models for each of communication situations listed in Figure 3 together with corresponding interfaces for connecting the processes of two or more designers. For such an approach a good starting point may be the work of (Khosravifar, 2013; Mulyar and van der Aalst, 2005a). This way a whole system for simulation and management of design parameter dynamics could be built from blocks considered as templates/patterns of generalised design process sequences. In this context, both design process models of manipulation arm assemblies could also be viewed and generalised as templates with following common elements: places for requirements and parameters; IN and OUT places for "interfacing" with other designers; activities for coupled parameters selection and parameters value check. The other activities in such template vary according to the specific design process for particular design task. We believe that such "template" based approach could be efficient in building a model of design parameter dynamics for the variant design of complex products including many variants that share relatively stable set(s) of parameters.

5 CONCLUSION AND FUTURE WORK

The aim of the presented research is to develop methods and tools which would enable consistent dynamic updating and propagation of updated design information in teamwork in a manner that will not generate additional tasks for designers. The research has been focused on management of design parameters, especially to issues that occur in collaborative teamwork when several designers work on a group of coupled parameters. Based on the presented simple case study we got the answer to the *third research question* - it can be concluded that "classical" (ordinary) Petri nets showed some significant drawbacks in modelling the design parameter dynamics because for any serious industrial application the generated nets would be too large. Coloured Petri nets, due to their concepts of data, time and hierarchy proved to be a much better method for modelling, simulation and visualization of design parameter dynamics. However, compared to ordinary Petri nets they require much more effort and training for designers to become "efficient expert" users. The models in Coloured Petri nets are sometimes too abstract and difficult to read and understand. This fact should not be neglected if we want to develop a method and tool which will not burden designers additionally.

Regarding *second research question,* in this phase we got only partial answers. One of the most crucial situations in design parameters dynamics is "resolving coupled parameters in teamwork", but this is surely not the only one. Based on results of presented case study and the work of (Mulyar and Van der Aalst, 2005a, 2005b) we believe that it is worthwhile to continue with the approach where repetitive patterns of communication situations and parts of the design process will be extracted by analysing information processing and information flows in complex product development environment. Further research efforts in this direction will be done in the large automotive company. This step will be based on empirical studies including modelling of information processing and information flows depending on the organizational and project context. The second step refers to creation, expansion and adaptation of the model for the consistent dynamic updating and propagation of the updated design information within the teamwork. For extracted repetitive patterns of partial processes, modelling and visualisation of dynamics will be conducted by Coloured Petri nets in form of generic templates. The desired result of this phase would be a simulator of selected communication situations and partial processes of teamwork activities within the dynamics of design parameter management. In the first phase, the implementation of the proposed model should be able to suggest and approve the automatic launch of small parts (sequences) of the process with the aim of gradual automatization of recognised information processing and information transferring activities. Possible extensions which would enable implementation of design process knowledge capturing and storing will also be considered.

The first research question should be further studied in the context of information systems being used in product development processes. The more complex the product is, the usage of different information systems (CAD, PDM, PLM, ERP, CRM) is more intensive and has more important role in the management of design parameter dynamics. Assuming that efficient CPN based model and tool for design parameter management is developed, its successful implementation in everyday practice and integration with other information systems still remains a great challenge.

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