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COLOURED PETRI NETS MODEL OF DESIGNERS COLLABORATION IN ITERATIVE RESOLVING OF COUPLED DESIGN PARAMETERS

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Abstract
The aim of the presented research is to investigate possibilities of applying Coloured Petri Nets (CPN) modelling methodology for supporting design collaboration with a focus on iterative resolving of coupled sets of design parameters. Two case studies have been conducted aiming to build CPN based models and simulations for design development projects having several sets of not trivially coupled design parameters. Based on the results, it is concluded that CPN-based approach could bring several significant benefits comparing to common design support methods and tools.

Keywords: coloured Petri nets, design parameters, design models, collaborative design, communication

1. Introduction
This paper presents the results of two case studies which were conducted to explore and support the reasoning in a broader research project which is aimed towards the enhancement of software support for design team collaboration (focused to design parameters) in complex and long-lasting new product development projects.
Permanently increasing the complexity of today's engineering activities requires adequate development and enhancement of supporting tools and methodologies which will enable the designers to deal with complexity more efficiently. The motivation for this research came from intensive discussions with design researchers from automotive industry. Those discussions emphasised the increasing significance of issues and problems in design practice that require synchronous design team communication and improved management of design process dynamics. Such issues in process dynamics are of special interest during reasoning and decision making processes in long-lasting NPD projects involving big and distributed teams. Presented study is a part of ongoing research cooperation of Faculty of Mechanical Engineering and Naval Architecture in Zagreb and the research centre of Daimler AG in Böblingen. This cooperation builds and continues on the long lasting research focused on issues of parameter management dynamics in the process of developing vehicle architecture (Toepfer and Naumann, 2016). Recent research in automotive industry (Königs, 2014; Toepfer and Naumann, 2016) confirms that PLM systems in the industry do not sufficiently address previously mentioned issues; they are not always able to 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. For products encompassing a large and complex network of interrelated design parameters, there are still many open issues showing drawbacks of software support systems. Karniel and Reich (Karniel and Reich, 2011a) emphasise that we cannot be sure that PLM systems could always ensure usage of properly updated product information in its operation. By analysing the current state of the art, it may be concluded that PLM systems still do not provide an adequate

and complete support for the dynamic tracking of parameter streams and communication processes in resolving final values of related, especially coupled parameters.

The presented research has been focused to improve the software support and methodology for iterative processes of resolving final values for sets of coupled design parameters. The authors consider that these are the crucial issues where drawbacks of PLM systems may be most influential in current design practice. Several authors introduced proposals for using Petri nets (Petri, 1962) and its extensions and variations in supporting design process from various viewpoints. In presented approach, it has been assumed that Petri nets will provide rich possibilities to formalise, visualise 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). Based on the analysed literature we expect that CPN based models would be much more efficient in supporting (partially even controlling) previously discussed issues comparing to PLM workflows and similar design process support tools. Since CPN include and unite concepts of data structures, hierarchy and time, they have widely been used in modelling, simulation and control of discrete event dynamic systems. We think that the abilities to respond to external events (signals), to trigger appropriate procedures immediately when requested conditions are met, together with programmable decision making, makes CPN a good candidate towards achieving a goal of immediate distribution of properly updated information.

Therefore, the aim of the presented research is to investigate possibilities of applying CPN modelling methodology for supporting design collaboration (and/or communication), with focus on iterative resolving of coupled sets of design parameters.

For this purpose, two case studies have been conducted aiming to build CPN based models and simulations for design development projects that don't consume large resources, yet each having several sets of (not trivially) coupled design parameters.

Previous discussions and analyses have generated the following research questions:

- *In what aspects could the appliance of CPN methodology to design process support eventually bring significant benefits and advantages comparing to common practice in industry?*
- *Is such an approach promising (in terms of generalisation and pattern recognition) as a strategy for building improved and more robust design support systems?*

The paper is structured in following sections: related work, basics of CPN methodology and toolkit, descriptions of design projects that have been the subjects of case studies, analysis of similarities in both realised models, detail presentation of one of the realised models, analysis of benefits comparing to the current industry practice, conclusions and further work in context of broader research scope.

2. Background and related work

The goal 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 and continues 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). All these papers emphasise 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 (Lindemann et al., 2009; Browning, 2016) 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.
Several 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.
Horvath et al. (2000) concluded that their results prove their fundamental hypothesis that the decision mechanisms behind design processes can be adequately represented in terms of predefined abstract activity patterns that can be easily represented by advanced Petri-net.
Topic et al. (2008) have explored improvements which can be achieved by applying Petri nets to the modelling, simulation and analysis of the software development process.

3. Basics of Coloured Petri Network methodology and "CPN Tools" toolkit

According to Jensen and Kristensen (2009) Coloured Petri Nets (CPNs) is a language for the modelling and validation of systems in which concurrency, communication, and synchronisation play a major role. Coloured Petri Nets is a discrete-event modelling language combining Petri nets with the functional programming language Standard ML. Petri nets provide the foundation of the graphical notation and the basic primitives for modelling concurrency, communication, and synchronisation. Standard ML provides the primitives for the definition of data types, describing data manipulation, and for creating compact and parameterisable models. A CPN model of a system is an executable model representing the states of the system and the events (transitions) that can cause the system to change state. The CPN language makes it possible to organise a model as a set of modules, and it includes a time concept for representing the time taken to execute events in the modelled system. "CPN Tools" is an industrial-strength computer tool for constructing and analysing CPN models.
Tokens in a CPN have a data value and have a timestamp attached to them. The data value, often called token colour, describes the properties of the object modelled by the token. The timestamp indicates the earliest time at which the token may be consumed. An example of simple CPN model is shown in Figure 1. In the net, two places may have float type tokens and one may have integer tokens. When the transition is fired (triggered), it will perform a predefined action.

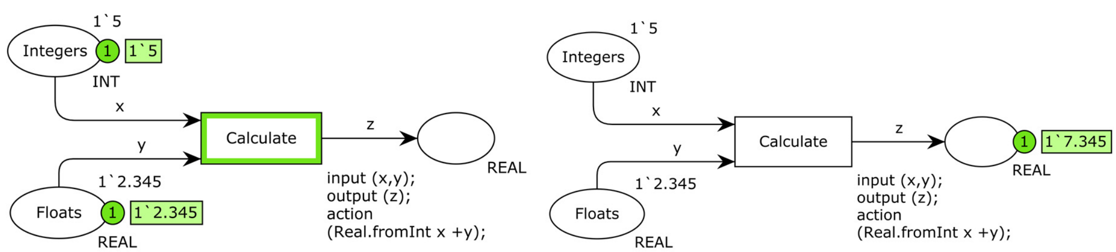

Figure 1. Basic features of Coloured Petri Nets

Typical areas of CPN application are simulations of communication protocols, data networks, business processes, production systems and similar. Interactive simulation allows to look at different outcomes and check if the model works as expected.

4. Design projects chosen for studying simulation of iterative resolving of coupled design parameters values in teamwork environment

Two design projects of relatively medium complexity have been chosen to study the application of CPN methodology to model and simulate the iterative processes which happen while design team is dealing with resolving of coupled parameters values.

Both design projects have been conducted by the same team of two excellent students in the final phase of their study at mechanical engineering design department. The complexity of the selected projects was on the level usually required for master thesis. Both designs were done as part of regular project based courses, while the research study presented in this paper was the subject of the master thesis for one of those students. The following two sections briefly explain the definitions and requirements for both design project tasks.

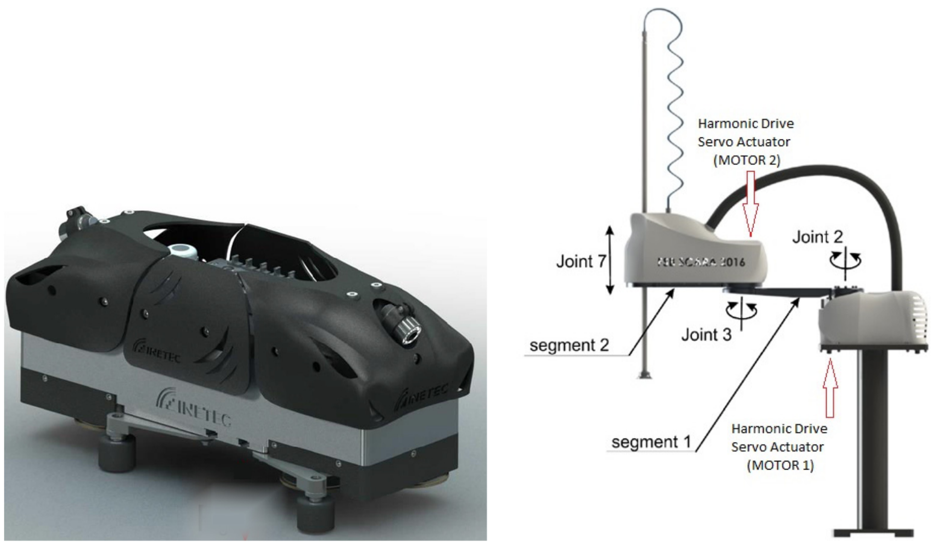

Figure 2. Devices whose design processes were the subjects of the case studies

4.1. Self-propelled device for cleaning the tank flange

The task in this project was to design a self-propelled device for cleaning the grooves on the water tank flange. The device must be able to self-adjust itself to the flange surface of the vertically mounted tank, which is 3 m under the water, and must be capable of visually inspecting and cleaning groove gaskets. It is necessary to vacuum and discharge particles from the flange surface during cleaning. It was necessary to consider the possibility of cleaning flanges with an inner diameter of 3180 mm and an outer diameter of 3492.5 mm. The expected continuous speed of the device was 700 mm/min. For the purposes of this research, the designs of two modules of this device were considered: the brush drive mechanism and the flange polishing mechanism. The design process has been divided to two designers - first has designed the flange polishing mechanism and the second has designed the brush drive mechanism.

4.2. Robotic manipulator type SCARA

The task in this project was to design the SCARA (Selective Compliance Articulated Robot Arm) type of robotic manipulator mechanism. The mass of the manipulated object was 100 g, the grip mechanism was vacuum type with compressed air as a medium. The projected area of the work space was 1.14 m^2, working height l = 0,82 m, and the angle of rotation 270º. The segments have had to be determined according to the projected surface. SCARA is a manipulator with two rotational and one linear joint. In this case study, the design process has been divided between two designers. The tasks of the first designer were: modelling of segment 2, dynamic analysis for starting the segment 2, selection of electromotor 2, linear motor and vacuum pump. After that, the first designer has to iteratively return to the modelling of segment 2 to adjust the segment dimensions to the dimensions of the selected electromotor. The first designer then has to forward particular parameters to the second designer who has to continue with following tasks: modelling of the segment 1, dynamic analysis of the entire manipulator and performing the FEM analysis. Designers have to agree upon the parameters that define the mounting of segments on electromotor 2. They must collaborate (preferably synchronous) to make a common decision and to adjust each of their sub-assemblies to the agreed design parameter values.

5. Analyses of studied design processes for preparation of initial states and data for building CPN models

In order to prepare the initial design states and input data for the proposed simulations, special consideration has been given to several aspects of design parameters management: derivation of parameters and their structure, analysis of the parameters determination sequences, the flow of parameters through the design project tasks, the relations between parameters and finally (most important) the determination of sets of coupled parameters.
The goal of the presented case studies was to model the collaboration of two or more designers on resolving values of coupled parameters. Therefore, for both devices the analysis of design parameter structure has been conducted with Design Structure Matrix (DSM) method (Eppinger et al., 1994), primarily to determine and extract the sets of coupled parameters. Since considered design processes were conducted by two designers, parameters were initially divided into two main sets, each of them "belonging" to one of the designers. This division has been derived accordingly to the distribution of design tasks between the two designers. Figure 3 shows the parameter-based DSM for SCARA robotic manipulator where each set (block) of design parameters is marked with different colour.

S1 - segment 1 S2 - segment 2 M1 - Harmonic Drive 1 (joint 1) M2 - Harmonic Drive 2 (joint 2)		SEGMENT 2 DESIGN, DRIVE DESIGN																	SEGMENT 1 DESIGN, SCARA CALCULATION										
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
SEGMENT 2 DESIGN, DRIVE DESIGN	**1** - the acceleration time of the second rotational joint	■																											
	2 - area of work space		■																										
	3 - the mass of the subject being moved			■																									
	4 - height of work space				■																								
	5 - the acceleration time of the translational joint					■																							
	6 - mass S2		X				■				X	X																	
	7 - moment of inertion S2		X					■			X	X																	
	8 - length S2		X						■																				X
	9 - max torque in joint 2 necessary for motion of S2	X	X	X			X	X	X	■																			
	10 -S2 diamater for bolting the M2 flange									X	■																		
	11 -number of bolt holes on S2 for bolting M2									X		■																	
	12 -moment of inertion M2									X			■																
	13 -mass M2									X				■															
	14 -M2 flange diameter for bolting the S1									X					■												X		
	15 -number of bolt holes on M2 for bolting S1									X						■												X	
	16 -mass of linear motor			X	X	X											■												
	17 -necessary vacuum			X														■											
SEGMENT 1 DESIGN, SCARA CALC.	**18** -the acceleration time of the main rotational joint																		■										
	19 -rotation angle of main joint																			■									
	20 -allowed bending stress for Al																				■								
	21 -mass S1			X																		■							
	22 -moment of inertion S1			X																			■						
	23 -max torque in joint 1 necessary for motion of S2			X			X	X	X				X	X					X	X		X	X	■		X			
	24 -max torque in joint 1 necessary for motion of S1			X			X	X	X				X	X					X	X		X	X		■	X			
	25 -length S1			X																						■			X
	26 -S1 diameter for bolting the M2 flange			X											X												■		
	27 -number of bolt holes on S1 for bolting M2			X												X												■	
	28 -maximum stress in manipulator's pillar			X				X	X								X				X	X		X	X	X			■

Figure 3. Parameter based Design Structure Matrix for SCARA robotic manipulator

Relations between parameters in the same block are marked with blue colour. Relations between parameters belonging to different blocks are marked with red colour. In such approach, two "levels" of coupled parameters may be distinguished:

- coupled parameters in the area of responsibility of one (single) designer;
- parameters that are "coupled between" two designers (or between two areas of responsibility) - marked with red colour on Figure 3.

Presented approach has been applied in the same way for both studied design projects. Here we have assumed that it is essential to distinguish those two "levels" or "processes" of dealing with coupled parameters. Why such a reasoning? Because we think that there are significant differences on how the designers approach resolving values of coupled parameters that are all under their control comparing to resolving coupled parameters that are being shared with another designer(s). Studying the second issue is actually the focal point of this research.
The further step in preparing the initial state for CPN simulation was the separate partitioning of the DSM blocks of each designer. This way we got the sets of coupled parameters in areas of responsibility

of each "single" designer. Those sets of coupled parameters on partitioned blocks of DSM for SCARA robotic manipulator are marked with orange colour on Figures 4 and 5.

SEGMENT 2 DESIGN, DRIVE DESIGN	1	2	3	4	5	8	16	17	6	7	9	10	11	12	13	14	15
1 - the acceleration time of the second rotational joint																	
2 - area of work space																	
3 - the mass of the subject being moved																	
4 - height of work space																	
5 - the acceleration time of the translational joint																	
8 - length segment 2		X															
16 - mass of linear motor			X	X	X												
17 - necesary vacuum			X														
6 - segment 2 mass		X										X	X				
7 - segment 2 moment of inertion		X										X	X				
9 - max torque in second joint needed for start of motion segment 2	X	X	X			X			X	X							
10 - segment 2 diameter for bolting motor 2 flange											X						
11 - number of bolt holes on segment 2 for bolting motor 2											X						
12 - motor 2 moment of inertion											X						
13 - motor 2 mass											X						
14 - motor 2 flange diameter for bolting segment 1											X						
15 - number of bolt holes on motor 2 for bolting segment 1											X						

Figure 4. Partitioned block of DSM for parameters of designer 1

SEGMENT 1 DESIGN AND SCARA CALCULATION	18	19	20	21	22	26	27	23	24	25	28
18 - the acceleration time of the main rotational joint											
19 - rotation angle of main joint											
20 - allowed bending stress for aluminium											
21 - segment 1 mass											
22 - segment 1 moment of inertion											
26 - segment 1 diameter for bolting the motor 2 flange											
27 - number of bolt holes on segment 1 for bolting motor 2											
23 - max torque in first joint needed for start of motion segment 2	X	X		X	X					X	
24 - max torque in first joint needed for start of motion segment 1	X	X		X	X					X	
25 - segment 1 length											X
28 - maximum stress in manipulator's pillar			X					X	X	X	

Figure 5. Partitioned block of DSM for parameters of designer 2

Here we have shown the DSM only for the design of the robotic manipulator, the results for the other studied device are very similar with identical reasoning and with the very similar overall number of design parameters as well as the structure and the number of the coupled parameters.

5.1. Structuring of CPN models for both case studies

Based on considerations and conclusions discussed in the previous section the further step was to determine the basic hierarchical structure for modelling the simulations of both studied design processes. The final result of structures of both realised CPN models is shown in Figure 6. Each block in shown diagrams represents one subnet, the green block is the main net on the top level of the hierarchy. According to reasoning explained in the previous section, for each of two designers separate models of their design processes (blue blocks) have been built.

Here we would like to emphasise that both case studies finally resulted in the same part of network structure that models (simulates) the process of the collaboration of two designers (three orange blocks). This is the desired and aimed situation that answers the second research question and it will be further discussed in conclusion.

"CPN Tools" tool provides two modes of running the simulation: "automatic" and "manual" - when user decides and "manually selects" which transitions (among available) will be executed in any model state.

Automatic mode executes the whole CPN model without any user influence. Of course, in this research we preferred the "manual" mode. CPN model provides the user with rich visualisation and tracking features for all situations and states that may occur during the process simulation. Those visualisation and tracking features may offer the user a very valuable support for making crucial decisions when "human intelligence" is necessary to control and influence the process flow.

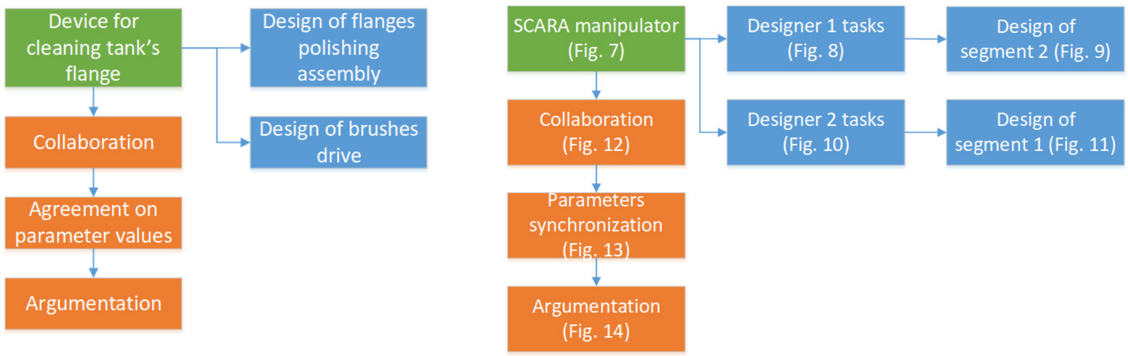

Figure 6. Hierarchical displays of both CPN models

6. Detailed explanation of the developed CPN model of designers collaboration on the example of SCARA robotic manipulator

This section contains the set of figures where each of them represents one part (block) of the hierarchical model structure shown in Figure 6 for SCARA robotic manipulator.

Each figure shows one particular net accompanied by an explanation of corresponding part of design process simulation. All figures in this section show specifically selected state spaces for each particular net that are not necessarily their initial states. Transitions that are enabled (ready to be executed) are marked with a green frame around them. Green rectangles represent the current states of data sets (colours). To get the deeper understanding of any CPN model it is recommendable to read introductory literature, especially (Jensen et al., 2009).

The design process starts with concurrent 3D modelling of both SCARA segments geometry. For the purposes of this case study we have made a simplest possible task distribution: the first designer models the segment 2, while the other models the segment 1 (Figure 7).

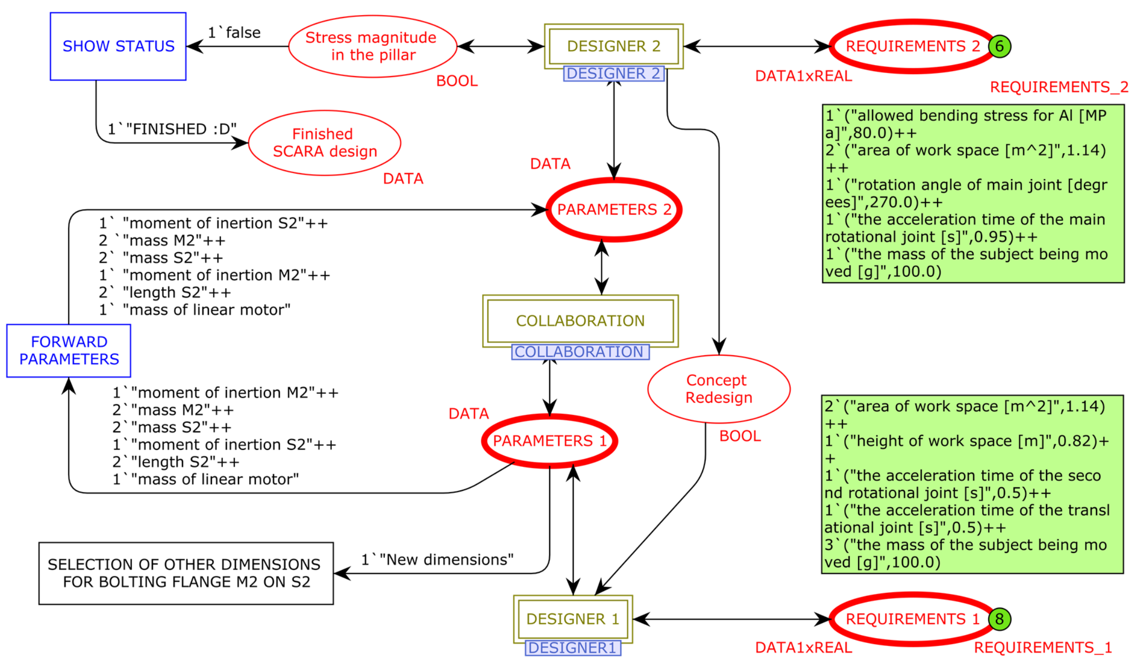

Figure 7. The main level of the CPN model of SCARA manipulator including design task distribution and parameter flow between two designers

Together with modelling of the segments geometry, designer 1 selects linear motor and vacuum gripper (suction pump) (Figure 8).

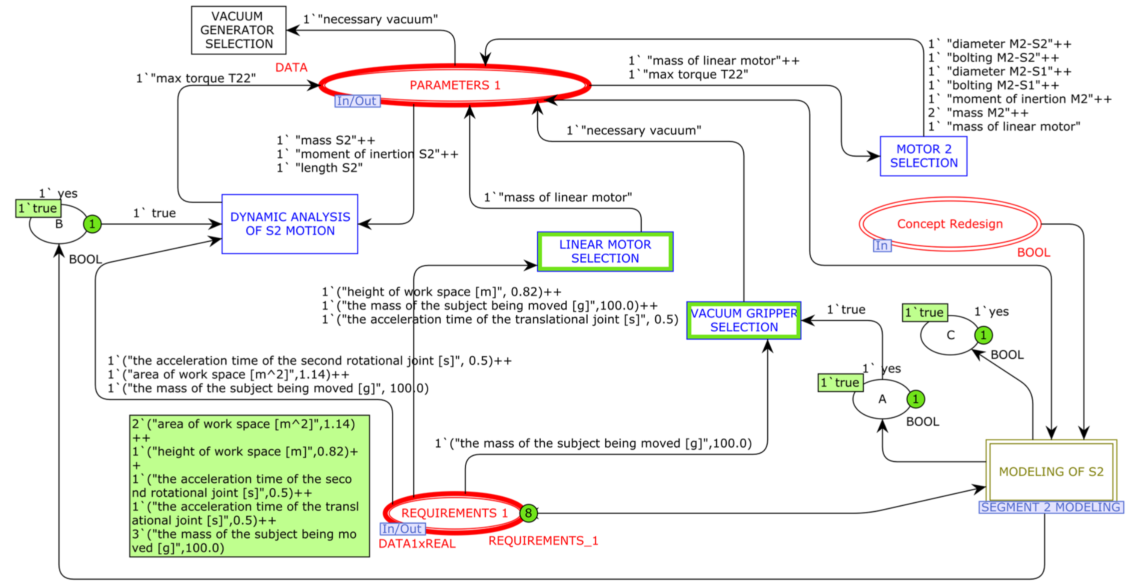

Figure 8. Design process (tasks) for designer 1

The proposed CPN model enables tracking of the values of length of segment 2 generated during the necessary iterations (Figure 9). This value is initially determined by the predefined random function in the given parameter range. Once the required parameters are determined, a dynamic analysis of segment 2 motion is performed, resulting in the required torque moments and the selection of motor 2. After that, the designer 1 is able to check whether the dimensions of the motor flange 2 correspond to the dimensions required for mounting the segment 2. If necessary, designer 1 may redesign segment 2 (Figure 9). The vacuum generator selection is performed concurrently with the enabled execution of transition for dynamic analysis of segment 2 movements (Figure 8).

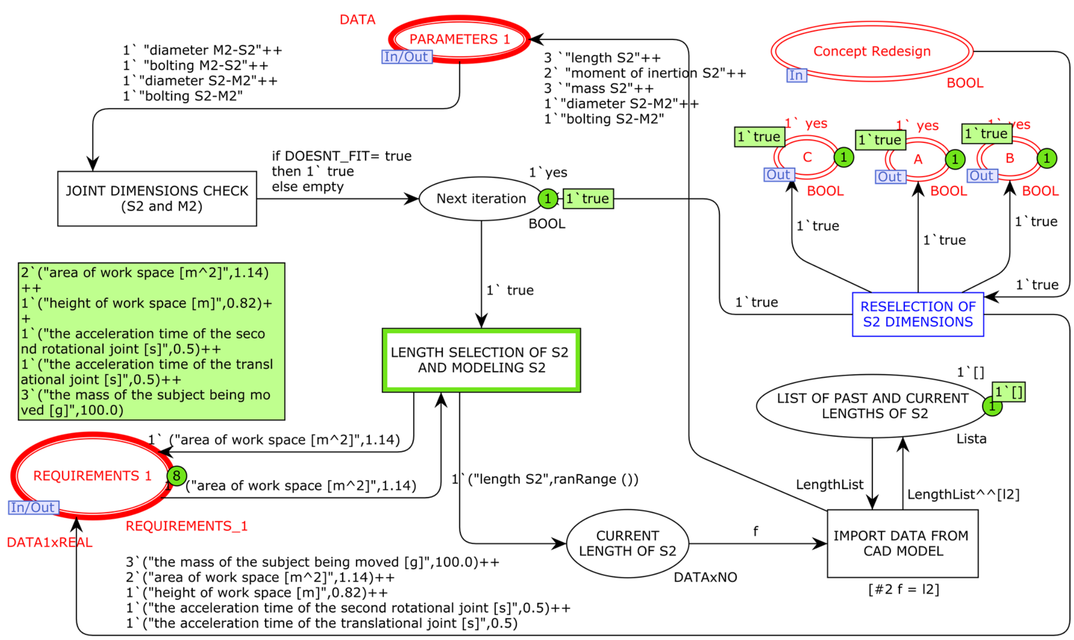

Figure 9. Segment 2 modelling (modelling S2 on Figure 8)

CPN place "Parameters 1" (on the main model level, Figure 7) now holds all the values that designer 1 needs to forward to designer 2 which are necessary to perform the dynamic analysis of the entire SCARA manipulator. Those sets of parameters also include coupled parameters.

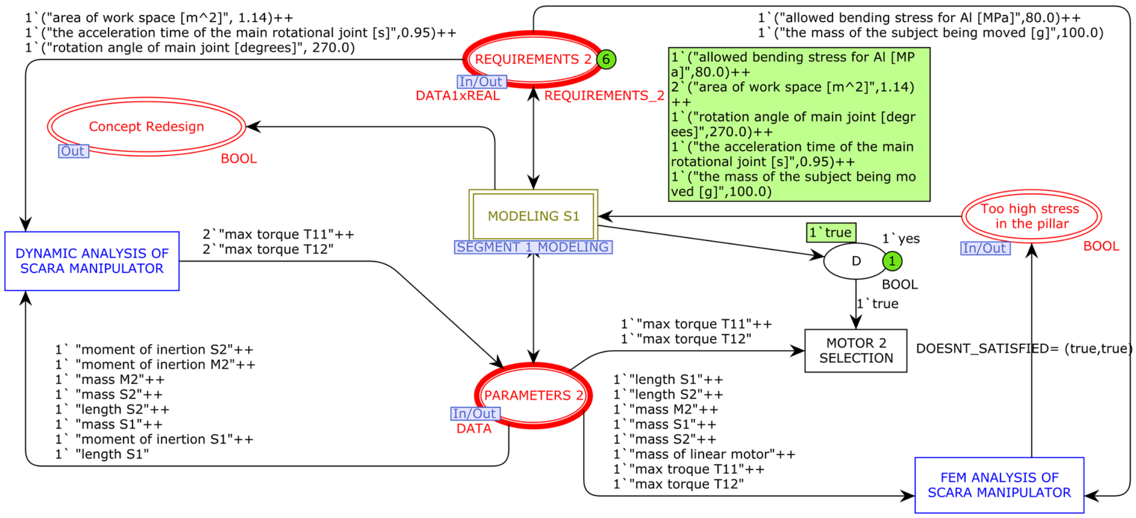

Figure 10. Design process (task) for designer 2

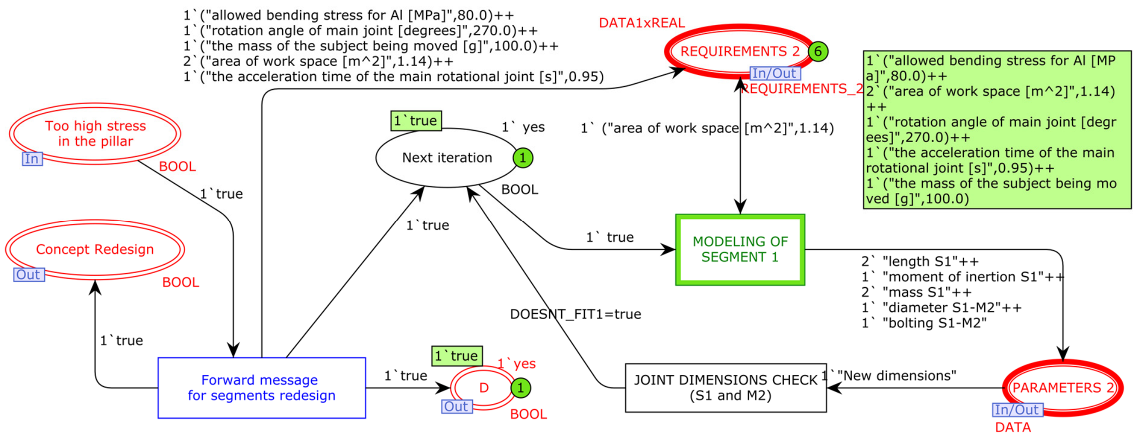

Figure 11. Segment 1 modelling (modelling S1 on Figure 10)

In this stage of the design process, it is possible and necessary to initiate the negotiation processes between two designers to coordinate the values of coupled parameters. This is the state of the process where designers need to start their collaboration (Figure 12) through iterative repeating of sub-processes of parameter value coordination and argumentation (Figures 13 and 14).

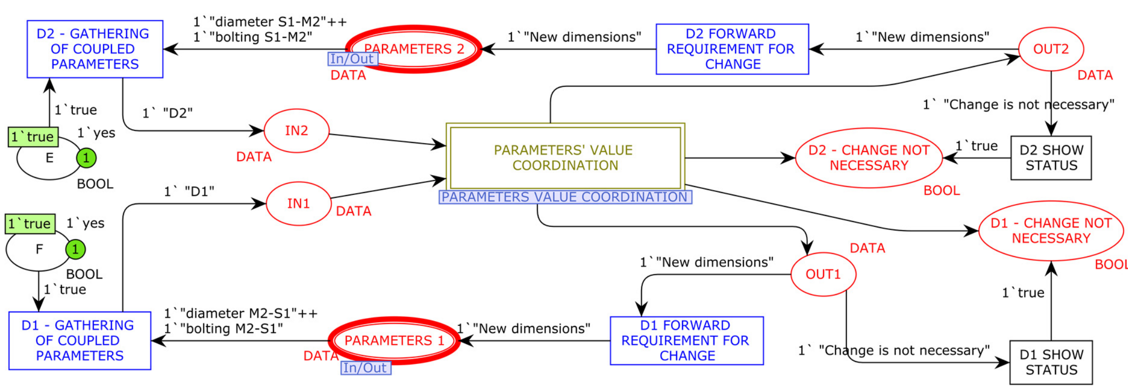

Figure 12. Model of the collaboration process for two designers

After retrieving the coupled parameters, a subnet for parameter value coordination is being initiated (Figure 13). The transition "Compatibility check" is executed to see if the values are already correct - if no changes are required, the corresponding message is sent. If it is necessary to negotiate and decide on the final values for realising the mounting of the **segment 1 on the motor 2 flange**, the subnet for argumentation is being activated (Figure 14). In the process of arguing each designer gives its own reasoning (design rationale) behind decisions for the current values of the coupled parameters.

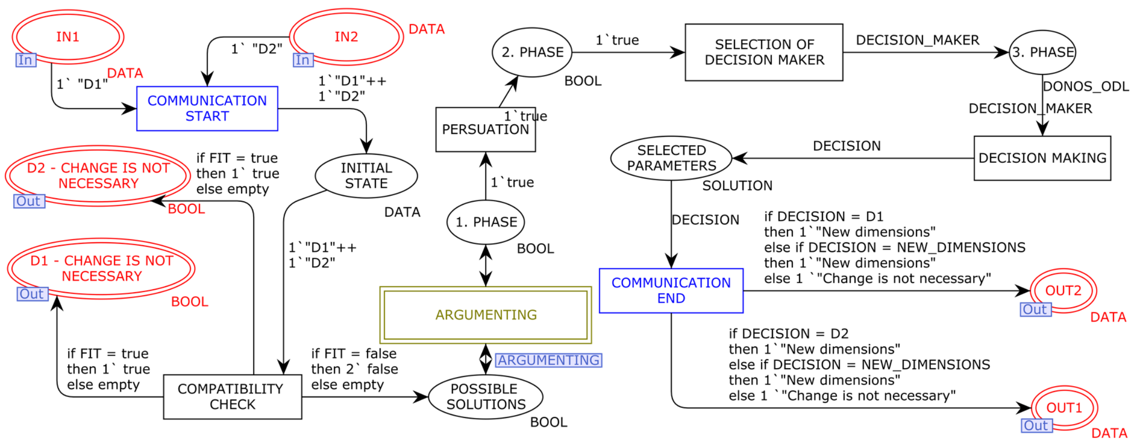

Figure 13. Model of parameters value coordination process for two designers

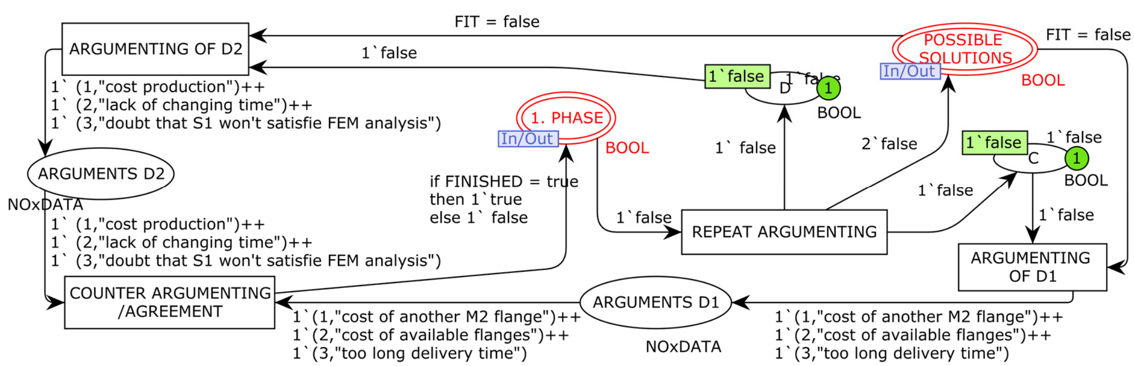

Figure 14. Model of the argumentation in the process of parameters value coordination

It is possible to repeat this process several times which is supported by the feedback loop (Figure 14). In the process of value coordination, the designers are trying to convince each other, the decision maker is defined (Figure 13) and the messages containing the final decisions are forwarded to each designer's network (places OUT1 and OUT2).

After negotiation process, designer 2 performs FEM stress analysis for the main column of the SCARA manipulator (Figure 10). If the stress is above permitted, the design process is going back to re-executing the processes (subnets) for modelling the segments 1 and 2. This re-modelling should change the segment 2 length in order to change the position of the motor 2 which generates the most of the flexing load of the main column of the manipulator. If the FEM analysis gives satisfying results, the process of designing the SCARA manipulator is finished.

When manually launching a simulation, it is possible to select the desired outputs of transition executions if there are variables on the output arrows. If the simulation is started automatically, variables are getting random values from the given ranges. The described model can trace the flow of parameters in the process of designing the whole product. The negotiation process on the values of the coupled parameters is also supported and fully traceable.

7. Conclusion and future work

The aim of the presented research is to investigate possibilities of applying CPN modelling methodology for supporting design collaboration (and/or communication), with focus on iterative resolving of coupled sets of design parameters. Only two studied cases could not be a sufficient basis for drawing convincing and reliable conclusions, however we argue that there is an evident possibility to generalise considered patterns (collaboration, value coordination and argumentation) for different design projects. This opinion is based on the following:

- the sub-nets (models) for these three patterns are identical in structure for both studied projects, they could be used for various similar situations just by changing input and output variables;
- based on the work of (Mulyar and van der Aalst, 2005a, 2005b) it may be concluded that CPN models are very suitable for the approach where patterns of sub-models are used to build generalised process models using "bottom up" approach.

These preliminary results give the positive answer to the second research question. To further explore this hypothesis, new case studies will be conducted that also should bring new insights for improvements and further development towards general usability and adaptability for broader domains. Presented CPN models (simulations) were worked properly, moreover, they were able to determine "final" values of coupled parameters in "automatic" execution mode. Coupled parameter values obtained in that way were far from optimal and reasonable problem solutions. If the simulations were executed manually, the users might get much better results. *So, where are the benefits, according to the first research question?*
Certainly, we can conclude that CPN-based approach could bring the following benefits:

- The collaboration process is "visualized" with method and tool that is developed especially for modelling dynamics of discrete-events process;
- such visual models certainly could contribute to the shared understanding in design teams
- particular part(s) of routine design activities (primarily simple communication and data transfers) could be automatized;
- since CPN include the time concept, especially in critical situations, the necessary communication (and/or data transfer) can be promptly initiated - which may lead towards the goal of "real time" updating of information;
- full traceability of collaboration process may be achieved using the embedded features of CPN that may record all the states and corresponding variable changes during the execution process.

It is important to note that in both case studies design parameters are coupled based on their interdependencies, not because of the allocation of tasks to the designers. If only one designer has worked on both examples, or there were more than two of them, this would not change in any way (except the number of people involved) the process of resolving the values of the coupled parameters.

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