INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016
Dubrovnik - Croatia, May 16 - 19, 2016.

MULTIDISCIPLINARY INTEGRATION DURING CONCEPTUAL DESIGN PROCESS: A SURVEY ON DESIGN METHODS OF CYBER-PHYSICAL SYSTEMS

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Keywords: cyber-physical systems, design method, multidisciplinary integration

1. Introduction

Cyber-Physical Systems (CPS) are firstly proposed by Helen Gill at the National Science Foundation in the US in 2006 [Baheti and Gill 2011]. The term of Cyber-Physical Systems refers to the integrations of computation with physical processes whose behaviour is defined by both cyber and physical parts of the systems [Lee and Seshia 2015]. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa [Wang et al. 2015]. Nowadays, CPS begin to focus on the integration of knowledge and engineering principles across the computational and engineering disciplines (network, control, software, human interaction, learning theory, as well as electrical, mechanical, chemical, biomedical, material science, and other engineering disciplines) to develop new CPS science and supporting technology [Baheti and Gill 2011]. Therefore, CPS are increasingly applied in the field of aerospace, defence, energy systems, healthcare, transportation, etc [Hu et al. 2016]. Concepts related to CPS are shown in Figure 1.
The definition and the application domains of CPS presented in Figure 1 indicate that the CPS design can be characterised as a multidisciplinary integration topic. The multidisciplinary integration topic, such as the design of mechatronic systems, has attracted the attention of both academia and industry for a long time [Zheng et al. 2015], and various multidisciplinary design methods of mechatronic systems have been proposed [Zheng et al. 2014]. However, such design methods may not be applied directly for the CPS design. One of the most significant reasons is that the multidisciplinary integration related to mechatronic systems are developed from electrical, electronic and mechanical engineering disciplines whereas CPS has initially been promoted from computation, communication and control engineering directions.
The paper aims at presenting the multidisciplinary integration during the conceptual design process exposed by existing design methods for CPS. In Section 2 the identified challenges related to the multidisciplinary integration during the conceptual design process for CPS are presented and discussed in details, and then the criteria to evaluate existing design methods are proposed by analysing the above challenges. Section 3 gives a review on existing design methods used for CPS. In Section 4, for a better understanding of the added value of every design method, the existing design methods are evaluated by the proposed criteria. The authors draw the conclusion and point out the directions for the future research in Section 5.

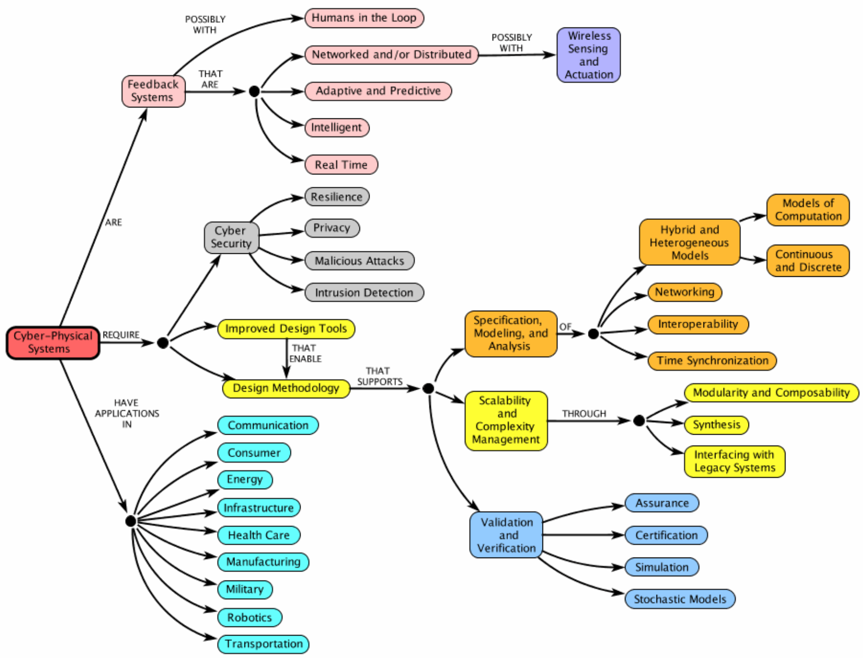

Figure 1. Concept map of CPS [Asare et al. 2012]

2. Multidisciplinary integration challenges during conceptual design process of CPS

As depicted previously, the CPS design urgently requires high-level integrated design methods in which the designers consider all the engineering disciplines simultaneously. Conceptual design process plays an important role for the designers and is considered as the foundation to enable the realisation of the final successful systems [Wang et al. 2002]. Duirng the conceptual design process, the designers generate solution concepts that will be employed in solving a given design problem and decide how to interconnect these concepts into system modelling [Komoto and Tomiyama 2012]. However, neither academia nor industry has yet provided explicit design methods to overcome the multidisciplinary integration challenges related to the conceptual design process of CPS. For the sake of clarity, the authors discuss the multidisciplinary integration challenges from the point of view of spatial dimension (disciplines represented by the horizontal axis) and temporal dimension (conceptual design process represented by the vertical axis) (Figure 2). These challenges will be discussed in more detail hereafter.

2.1 Challenges and criteria derived from multidisciplines

In this paper, the challenges derived from multidisciplines are proposed from the point of view of spatial dimension. One of the most important reasons is that the CPS design requires a multi-disciplinary development process and the designers of different disciplines are often geographically distributed. During the design process of CPS, the designers should focus not only on the separate physical components and computational components, but also on the integration and interaction of them. Therefore, the authors point out the challenges related to the CPS design from the physical process perspective, the computation perspective and their integration perspective respectively.

- From the physical process perspective, CPS link directly with the physical world. They detect the environmental changes and realise the real-time control of the system behaviour. Compared with other traditional complex systems (e.g. mechatronic systems), the environmental influences (i.e. variances and uncertainties in environment or created by human beings) plays a significant role for CPS [Grimm et al. 2014].
- From the computation perspective, CPS are considered to be developed based on the embedded systems [Lee and Seshia 2015]. However, the link to physical world of CPS is much stronger

than that of embedded systems. Therefore the software of CPS is much larger and more complex than that of the embedded systems.

- From the perspective of the integration of computation and physical processes, the CPS design requires a heterogeneous integration for the collaborative design process of CPS. On the one hand, physical components and computational components interact with each other between disciplines. This leads to the interruptions and incompatibilities across the disciplines during the design process. On the other hand, there is a lack of clearly specified and documented interactions and interfaces between the various disciplines and involved components. Hence mutual understanding in communication is hindered [Grimm et al. 2014].

By analysing these challenges related to disciplines, three criteria to evaluate current design methods can be proposed as follows:

- Cr.1: From the physical process perspective, does the design method consider the environmental influences (i.e. variances and uncertainties in environment or created by human beings) during the design process?
- Cr.2: From the computation perspective, does the design method consider the strong link between the software of CPS and physical world during the design process?
- Cr.3: From the perspective of the integration of computation and physical processes, does the design method consider the heterogeneous integration between the physical components and the computational components during the design process?

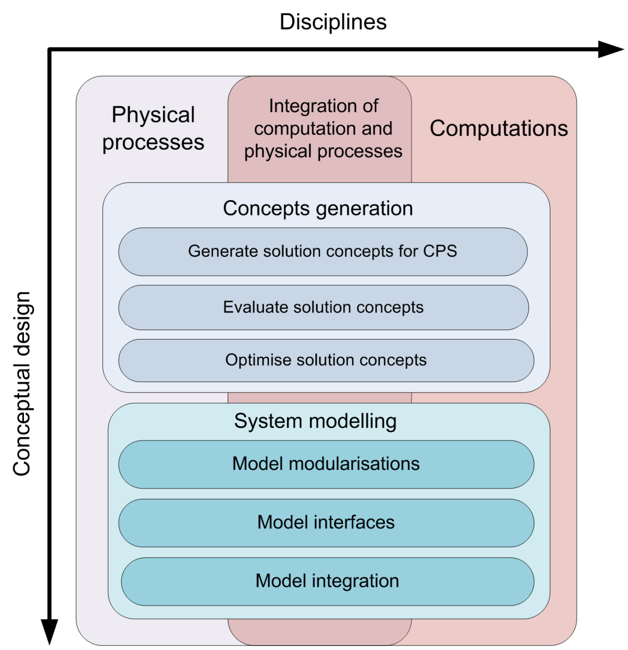

Figure 2. Disciplinary integration during conceptual design process

2.2 Challenges derived from design phases

Current research and practice experience show that there is a lack of tools and methodological support to handle the complexity of the CPS design in the conceptual design process of CPS [Anderl et al. 2013]. In the conceptual design process, designers select concepts that will be employed in solving a given design problem and decide how to interconnect these concepts into an appropriate system model. As a result, from the point of temporal dimension, the authors discuss the challenges exiting in the conceptual design phase and system modelling phase.

- From the perspective of concepts generation, the design-characteristic aspects of systems, such as hierarchy parameters, modularity of the design should be analysed by using of conceptual model [Hehenberger 2012]. The solution concepts for the CPS design should be proposed at the end of the conceptual design phase. Three main challenges exist in the conceptual design phase as follows. The first one is how to generate the solution concepts by collecting the customers' requirements or the market survey result. Although various tools and languages have been proposed to structure the customers' requirements [INCOSE 2010], however, the process from the requirements specification to the solution concepts should be detailed. Moreover, different solution concepts can be proposed by different designers according to their background knowledge and professional experiences. Therefore the second challenge is how to evaluate the different solution concepts previously proposed. Finally, due to the complexity of CPS, it is impossible to find the optimum solution concepts without iterations. As a result, the last challenge is how to optimise the solution concepts during the conceptual design process.

- From the perspective of system modelling phase, CPS may be defined as an assembly of components and the interfaces among them. The objective of the system modelling phase is to set up a cross-multidiscipline model to determine the important parameters and realise the potential optimisation [Hehenberger 2012]. However, the cross-multidiscipline models created during the modelling phase of the CPS design process are hindered three main challenges. According to the definition of CPS, models of CPS normally include physical components and computing components [Lee and Seshia 2015], so first challenge is how to model the components of different disciplines. The second challenge is how to model the interface among the components of different disciplines with a common terminology. The last challenge is related to the model integration. Established techniques exist to model the physical dynamics of physical components (i.e., continuous model) and the discrete behaviours of computing components (i.e., discrete model), but the interface to join the continuous model and discrete model has not been paid enough attention.

By examining the challenges related to the concepts gereration and the system modelling, six criteria to evaluate the design methods can be identified.

- Cr.4: Can the design method be used to generate the solution concepts?
- Cr.5: Can the design method be used to evaluate the different solution concepts?
- Cr.6: Can the design method be used to find the optimum solution concepts?
- Cr.7: Does the design method support to model the components of different disciplines?
- Cr.8: Does the design method support to model the interface among the components?
- Cr.9: Does the design method support the model integration (continuous model and discrete model)?

In this section, the criteria to evaluate the existing design methods of CPS have been proposed by analysing the multidisciplinary integration challenges. Next section will review the existing design methods of CPS.

3. Design methods of CPS

CPS design requires a multidisciplinary collaboration. To deal with such multidisciplinary design issue, since the late 1950s, system engineering has been proposed as an interdisciplinary approach to design complex systems. International Council on Systems Engineering (INCOSE) defines systems engineering as "an interdisciplinary approach and means to enable the realization of successful systems" and means to enable the realisation of successful system [INCOSE 2015]. Nowadays, the design methods based on traditional systems engineering approaches, such as V-model, the design methods derived from Model-Based Systems Engineering (MBSE) and the much recent agile development, many design methods for CPS have been proposed. A non-exhaustive list of design methods is presented hereafter.

3.1 Design methods based on V-model

The V-model presents a general flow for the product development process. It starts with identification of user's requirements. Once the requirements have been taken into account, they are then placed under project control (left branch of the V-model) and the V-model will end with a user-validated system (right branch of the V-model). In order to arrive to the final product, each stage of the product definition should be tested [Forsberg and Mooz 1998]. However, as previously depicted, the V-model provides a general development flow. The integration of physical components and computational components has not been taken into consideration. Moreover, the design phases should be detailed according to the particularities of CPS.

Focusing on the design of embedded systems which are considered as the foundation of CPS [Lee and Seshia 2015], the SPES 2020 method further decomposes the left branch of V-model and proposes the detailed design phases. The SPES design method emphasises the following viewpoints to support the conceptual design process of embedded systems, starting with requirements through to concrete technical solutions: requirements view, functional view, logical view, and technical view [Pohl et al. 2012]. However, the SPES 2020 method is proposed for the design of embedded systems, the physical components of CPS have not been paid enough attention.

Grimm et al. proposed a conceptual approach based on the SPES design method [Grimm et al. 2014]. The conceptual approach extends these views proposed by SPES 2020 method by considering the physical behaviour of CPS as well as human. Six abstraction views for the conceptual design phase of CPS are requirement structure, functional structure, logical structure, technical structure, human viewpoint, system behaviour.

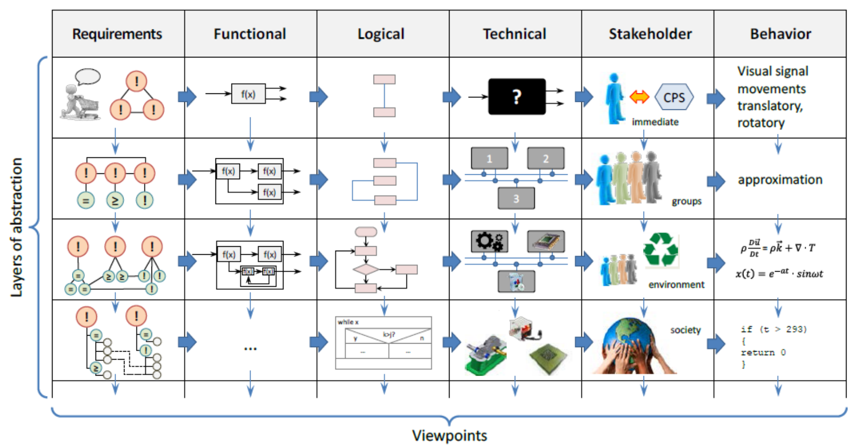

Figure 3. CPS abstraction in different viewpoints modified based on SPES 2020 [Grimm et al. 2014]

In this sub-section, design methods of CPS based on the traditional system engineering approach have been presented. Nowadays, Model-Based Systems Engineering (MBSE) has gradually becomes the main stream method for complex systems engineering [Fisher 2008]. The design methods of CPS based on MBSE will be reviewed in next sub-section.

3.2 Design methods based on MBSE

MBSE has been widely used for complex system design nowadays. One of the greatest advantages of MBSE is that the knowledge can be expressed and shared unambiguously between the engineers and different stakeholders with the help of the models. Additionally, the MBSE facilitates dependency tracing between different models and the reuse of knowledge [Cao et al. 2011]. The paper generally divides the design methods based on MBSE into three types: design methods based on modelling languages, design methods based on ontological modelling approaches and design methods based on modelling tools.

3.2.1 Design methods based on modelling languages

A standard systems modelling language, the Systems Modelling Language (SysML), has been established based on unified modelling language (UML) to support the MBSE by the International Council of Systems Engineering (INCOSE) and the Object Management Group (OMG) [2009]. Thramboulidis proposes a method to model the cyber-physical components based on SysML. The architecture model of CPS proposed by Thramboulidis is considered as a composition of cyber-physical components resulting from the SysML-view model. In addition, SysML ports are used to represent the interaction points of the cyber-physical component with its environment. The type of the port specifies features available to and requested from the external entities via connectors to the port [Thramboulidis 2015].

Other modelling languages have been proposed to model the CPS. Venter and Ehlers believe that it is not possible to formally describe dynamic CPS due to the flexibility in which incomplete UML diagrams can be defined, so they propose an Architecture Description Language (ADL) for dynamically modelling architectures with specific reference to CPS [Venter and Ehlers 2014]. A highly dynamic and distributed autonomous architecture can be described by the ADL.

One of the main limitations of previous modelling language is that it is hard to evaluate and optimise the solution concepts previously proposed because the system models based on UML/SysML or ADL are described with qualitative models, and designers need quantitative models to evaluate the performance of proposed solution concepts. Modelica is another discipline-independent system modelling language which can be used to support the MBSE [Fritzson and Engelson 1998]. However, unlike the modelling language such as UML/SysML or ADL, Modelica not only can represent one system's model, but the model created in Modelica can be transferred into mathematical models for simulation solving as well. Several CPS design methods based on Modelica are described in [Fritzson 2011], [Henriksson and Elmqvist 2011], [Feng and Zhang 2014], [Nazari et al. 2015].

3.2.2 Design methods based on ontological modelling approaches

The second type of MBSE based design method reviewed in this sub-section is ontology-based design method. Ontology-based product modelling approaches have been widely used for complex product development in a collaborative environment because they can provide a successful semantic interoperability to help the designers achieve the basis of seamless communication and thereby enable better integration of different disciplines [Patil et al. 2005]. Paul et al. propose an ontology-based integrated assessment framework [Paul et al. 2008]. In this framework, system entities can be categorized into computer platform, devices, communication channels, human and information application software. Petnga and Austin propose temporal semantics and their central role in the development of a new time-based reasoning framework in MBSE for CPS. In their proposition, an ontological framework describes the system behaviour in terms of time, intervals of time, and relationships among intervals of time, and the correctness of functionality with respect to requirements can be assured [Petnga and Austin 2013]. Lin et al. proposed an agent-based modelling for CPS to help the designers to solve the problems resulting from the fundamental differences in the operation of cyber and physical components and significant interdependencies among these components [Lin et al. 2010].

3.2.3 Design methods based on modelling tools

Besides the design methods based on the modelling languages and the ontological modelling approaches, several design methods based on commercial multi-discipline modelling and simulation software, such as MATLAB [Al Faruque and Ahourai 2014], AMESim [Canedo et al. 2014], are developed to support the design method of CPS based on MBSE. Like Modelica, the modelling software provides various types of libraries of different disciplines to help the designers valid, evaluate and optimise their design.

In this sub-section, several design methods based on MBSE have been reviewed. Next sub-section will present the design methods of CPS based on the much recent agile product development.

3.3 Agile methods for CPS

Agile development methods were seen initially as software engineering methods in which requirements and solutions evolve through collaboration between self-organising, cross-functional teams [Highsmith 2002]. They were initially viewed as best suited to small and non-critical projects with co-located teams [Abrahamsson et al. 2009]. Therefore how to apply the agile development methods to the CPS design is still a great challenge for the designers. On the one hand, the CPS design is often considered as a large-scale project and the designers are often separated in different areas. On the other hand, the design

process of CPS always requires a regulated environment in which the design process is expressed and adapted by careful tailoring.
Specific methods have been proposed according to the principles of agile development. How to use them during the design process of CPS has attracted more and more attention and research. Scrum, one specific method of agile development, is originally suggested for "managing product development project" and mainly used for software development projects [Boehm 2002]. Mulder et al. probes the application of Scrum as agile development method to realize a cyber-physical system with a multidisciplinary team [Mulder et al. 2014]. They believe that the traditional separation of computation (software) from physicality (hardware) does not work for CPS. Therefore the physical component platform is complemented by five computing sub-platforms namely netware, hardware, software, firmware, and knowledgeware sub-platforms. It forced the project teams of different disciplines to focus on usability and domain knowledge that is iteratively assessed by the client or focus groups. Furthermore, a Scrum board establishes a physical planning instrument that all team members and other stakeholders can access and understand (Figure 4).

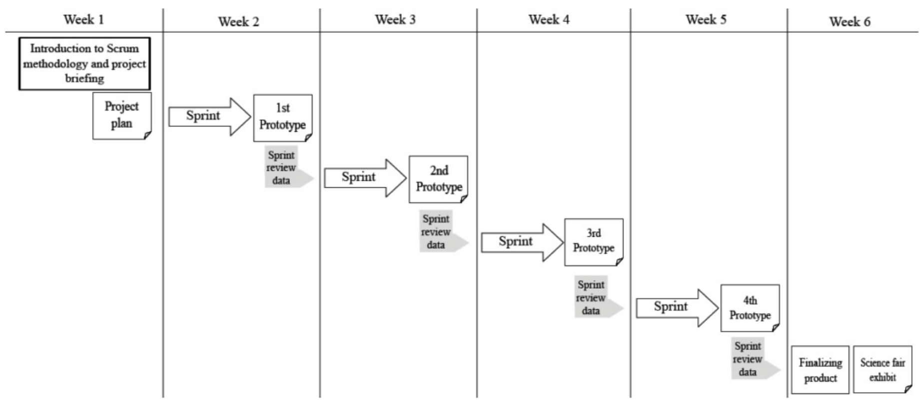

Figure 4. Planning of the Scrum team [Mulder et al. 2014]

This sub-section has reviewed the agile design methods for CPS. An agile design method based on Scrum proves to be an effective support for the collaboration of the individual designers and the coordination of resources and designers during the whole development process, but it is too generic and does not provide the effective and detailed solutions to overcome the challenges related to the conceptual design phase and system modelling phase of the conceptual design process.
Numerous design methods for CPS have been presented in the above section. The proposed criteria will be used to assess the different design methods in the following section.

4. Assessment of studied design methods

Several design methods have been surveyed in previous section. The authors have discussed the multidisciplinary integration challenges from the point of view of spatial dimension (disciplines represented by the horizontal axis) and temporal dimension (design process represented by the vertical axis). As to the view of spatial dimension, three criteria have been proposed by considering the multidisciplinary integration challenge. Table 1 shows the assessment of the studied design methods according to the proposed criteria related to disciplines. The V-model provides a general development flow; however, the integration of physical components and computational components has not been taken into consideration by the traditional V-model. The SPES 2020 method is developed based on V-model, but it emphasises the conceptual design process of embedded systems. Therefore little attention has been paid on to the physical process perspective. Grimm et al. proposed the conceptual approach which considers the physical behaviour of CPS as well as human. The design methods based on MBSE can be generally divided into three types: design methods based on modelling languages, design methods based on ontological modelling approaches and design methods based on modelling tools. The assessment results presented in Table 1 shows that none of them can perfect answer the research questions proposed by the three criteria. The agile methods for CPS, such as the agile method proposed by Mulder et al. based on Scrum method, force the project teams of different disciplines to collaborate to deal with the combination of computation (software) and physicality (hardware). However, the detailed design process to achieve the multidisciplinary integration has not been presented.

Table 1. Assessment of studied design methods by the criteria related to disciplines

	Cr.1	Cr.2	Cr.3
V-model	No	No	No
SPES 2020 method	Partial	Yes	Partial
[Grimm et al. 2014]	Yes	Yes	Partial
[Thramboulidis 2015]	Yes	Partial	Yes
[Venter and Ehlers 2014]	Partial	Yes	Partial
Design methods based on Modelica	Partial	Partial	Partial
[Paul et al. 2008]	Yes	Yes	Partial
[Petnga and Austin 2013)	Partial	Partial	Partial
[Lin et al. 2010]	Partial	Partial	Yes
Design methods based on modelling tools	Partial	Partial	Partial
[Mulder et al. 2014]	Partial	Partial	Partial

Table 2 shows the assessment of the studied design methods according to the proposed criteria related to process respectively. The design methods based on Modelica or based on modelling tools cannot help the designers to generate the solution concepts due to the limitation of describing the customers' requirements. However, both of them can be used as an effective support to evaluate the exiting solution concepts and to find the optimum one because they can provide quantitative models to help the designers to evaluate the performance of each solution concept. As to the system modelling, all the reviewed design methods can support to model the components of different disciplines; however, how to model the interfaces among the components should be further studied. Although the integration of continuous model (physical components) and discrete model (discrete model) has been taken into consideration by some of the existing design methods (e.g. SPES 2020, design methods based on Modelica, etc), attention should be also paid to this issue in the future.

Table 2. Assessment of studied design methods by the criteria related to process

	Cr.4	Cr.5	Cr.6	Cr.7	Cr.8	Cr.9
V-model	Partial	No	No	Yes	No	No
SPES 2020 method	Yes	No	No	Yes	Partial	Partial
[Grimm et al. 2014]	Yes	No	No	Yes	Partial	Partial
[Thramboulidis 2015]	Yes	No	No	Yes	Partial	No
[Venter and Ehlers 2014]	Yes	No	No	Yes	Partial	Partial
Design methods based on Modelica	No	Partial	Partial	Yes	Partial	Partial
[Paul et al. 2008]	Yes	No	No	Yes	Partial	No
[Petnga and Austin 2013]	Yes	No	No	Yes	Partial	No
[Lin et al. 2010]	Yes	No	No	Yes	Partial	No
Design methods based on modelling tools	No	Partial	Partial	Yes	Partial	Partial
[Mulder et al. 2014]	Yes	Yes	Yes	Partial	Partial	Partial

5. Conclusions

The first conclusion to be pointed out is that different design methods of CPS have been proposed up to now. However, from the evaluation discussed in this paper, the existing design methods cannot help the designers to overcome the CPS design challenges. As a result, the second conclusion is that a design method which can fully support the multidisciplinary integration during the conceptual design process of CPS should be further developed in the future.

According to the assessment results of exiting design methods, the future work can be generally divided into two parts. The first part is related to the multidisciplinary integration. CPS are considered as the integration of computation and physical processes. However, the evaluation results of Table 1 shows that none of the design methods can fully achieve the multidisciplinary integration from the perspective of physical process, computational process or the interaction of them. A research potential can be indicated by Table 1. Synergetic combination of the existing design methods may help the designer to achieve the multidisciplinary integration by considering the evaluation results from the three perspectives. The second part is related to the conceptual design process of CPS. As to the concepts generation, although almost all existing design methods support the generation of solution concepts, but how to evaluate and optimise the solution concepts should be further studied. As to the system modelling, a hybrid modelling method in which the designers can simultaneously create continuous model for the physical components and discrete model for the computational components should be developed.

Acknowledgement

This work has been partially supported by the Doctoral Program of Chinese Scholarship Council and the Austrian Center of Competence in Mechatronics (ACCM) / Linz Center of Mechatronics (LCM) in the framework of the Austrian COMET program. It also takes place in the scientific strategy of Labex MS2T supported by the ANR - French National Agency for Research.

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