Proceedings of TMCE 2014, May 19-23, 2014, Budapest, Hungary, Edited by I. Horváth, Z. Rusák

DUAL-ASPECT MODEL FOR FAILURE FORECASTING IN CYBER-PHYSICAL SYSTEMS

Santiago Ruiz-Arenas
Faculty of Industrial Design Engineering
Delft University of Technology
The Netherlands
Grupo de Investigación en Ingeniería de Diseño
Universidad EAFIT
Colombia
s.ruizarenas@tudelft.nl and sruizare@eafit.edu.co

Imre Horváth
Eliab Z. Opiyo
Faculty of Industrial Design Engineering
Delft University of Technology
The Netherlands
{i.horvath, e.z.opiyo }@TUDelft.nl

Ricardo Mejía Gutierrez
Grupo de Investigación en Ingeniería de Diseño
Universidad EAFIT
Colombia
rmejiag@eafit.edu.co

ABSTRACT

Cyber physical systems (CPSs) are complex systems whose performance depends on the interactions between heterogeneous subsystems, the external environment, and the interrelation between the natural systems and its cyber-physical augmentations. Any fault that occurs during these diverse and interrelated interactions may cause failure or a malfunction of the entire system. The traditional multi-aspects modeling techniques developed for analyzing complex system performance can to some extent fundamentally be used in the analysis of CPSs. The problem, however, is that these modeling techniques do not consider the consequences of the integration of natural systems and cyber-physical augmentations. In this article, we propose a novel dual-aspect modeling technique that integrates natural and CPSs functional systems. This modeling technique includes natural systems, such as plants and humans as integral parts of the system, and therefore allows us to study their interactions, influences and effects. A cyber-physical greenhouse case study is presented to demonstrate the applicability of the proposed modeling technique. The proposed dual-aspect modeling technique will be used in the subsequent stages of our research to analyze and understand the interactions between natural systems and CPS augmentations with a view to identify influential factors of failure in system operation as well as the cause and types or modes failures.

KEYWORDS

Dual-aspect modeling, multi-abstraction, multi-level modeling, cyber-physical systems, greenhouse modeling

1. INTRODUCTION

Multi-aspect models have widely been used for modeling of the behavior of systems [1], [2], [3]. They allows consideration of the effects of diverse variables involved in the operation of systems in singular or in interconnected representations, thereby providing a wider overview of their behaviors and compositions. Complex systems such as cyber-physical systems (CPSs) are heterogeneous systems whose operations are substantially influenced by multiple changing factors such as synergetic operation of different subsystems, the effect of external factors such as the environment, and the interrelationships between natural systems (such as living organisms) and the artificial systems. Any fault in any of the subsystems may cause a failure or malfunction in the system and affect system operation and availability. Therefore, we argue in this paper that a multi-aspects modeling technique is required for analyzing performance of CPS, as well as for establishing maintenance strategies that can contribute to increase system availability.

Several multi-aspects modeling techniques are presently used in areas such as software engineering and business process management [4], [5]. However, these modeling techniques cannot holistically and comprehensively consider all possible perspectives and interactions involved in complex systems with the level of complexity of CPSs. New modeling techniques for modeling and representing the interactions between the physical and cyber part are therefore required [6]. These new techniques should allow effective and comprehensive descriptions and representation of natural systems as well, including representation of the manifestation of natural entities and their interaction with other constituent components of CPSs.

In CPSs, new services are expected to be provided through the cyber-physical augmentation of natural systems. We consider a CPS to be made up of natural systems and cyber-physical augmentation. Therefore, the interrelation between the natural and augmented elements of systems should properly be represented in a dual-aspect model. The modeling technique we are proposing blends into the same representation the objectives, functional and structural characteristics of the natural and cyber-physical systems. This integration will allow us to analyze the interactions between the elements from both cyber-physical and natural perspectives of the system.

This paper presents the proposed dual-aspect modeling technique. It is organized as follows. A concise literature review on multi-abstraction modeling techniques is presented in Section 2. Then, the concept of dual-aspect modeling is introduced in Section 3. An application case study in cyber-physical greenhouse is presented in Section 4. And finally, the discussion and some conclusions about the proposed modeling technique are presented in Section 5.

2. REVIEW OF THE EXISTING MULTI-ABSTRACTION MODELING TECHNIQUES

There are several types of multi perspectives modeling techniques that includes into their schemes multi perspectives analysis in the literature. These techniques are used in two main application domains: (i) technological systems modeling, and (ii) enterprise systems modeling. Technological systems include technical engineering systems, interactive engineering systems and autonomous engineering systems. The main characteristic of these systems is that they are technical artifacts that are connected to the environment by means of inputs and outputs [7]. These systems are typically analyzed from a technical perspective, focusing on the system performance and other desirable characteristics. Software products can also be included in this category. By contrast, enterprise systems are focused on the organizational aspects or entities, including customers, suppliers and employees, and the information flows between these entities is the most relevant aspect [8]. In this category, there are multiple types of systems focused on various domains related to the organization, such as cultural, scientific, political, and economic spheres. From the perspective of multi-aspects or perspective modeling, technological systems and enterprise systems are addressed differently. In technological systems, multi-aspect models seek to provide a multiple view on a system or its domain by using multiple representation schemes [9]. In enterprise systems different abstraction levels are typically used to support the processes of designing corporate information systems and in describing corporate strategies, business processes and resources information [10].

From the technological systems perspectives, Pahl and Beitz propose a multi-perspective modeling of technical artifacts that includes flows of information, material or physical entities, and energy [7]. They consider “functions” as the means of analysis and include multiple levels, which also include sub-functions and auxiliary functions. They argue that technical systems should have the main type of flow, which can be energy-based, material-based or signal/information -based. Therefore, for example, they classify machines as energy-based, apparatus as material-based and devices as signal/information based. We argue, however, that the latter classification does not apply to CPSs as they are heterogeneous systems that may include in the same level machines, apparatus and devices as components of the system. UML is another modeling technique developed for specifying, visualizing, constructing, and documenting the artifacts of a system-intensive process [11]. This modeling technique provides nine different type of diagrams [12] which represent different perspective abstractions, which are: (i) class diagram, (ii) sequence diagrams, (iii) collaboration diagrams, (iv) object diagrams, (v) state-chart diagrams, (vi) activity diagrams, (vii) use case diagrams, (viii) components diagrams, and (ix) deployment diagrams. Another well-known technique developed for analyzing technological systems is IDEF [13]. It includes activity function modeling, entity-relationship modeling, designing relational database, process description, object oriented design methods and ontology description capture method [14]. These levels of abstraction allow us to consider different focus during system design. These characteristics make these techniques also suitable for enterprise modeling.

Some of the methods described above, such as UML and IDEF, developed from the technological system perspective can also be applied for enterprise modeling. However, some publications such as [10] argue that techniques such as UML have in the first place been designed for use in software development and therefore they don't provide suitable basis for developing enterprise models (concepts or graphical representations). Therefore, as a result, modeling techniques like Aris have instead been developed specifically for business process management. The Aris modeling technique allows, e.g., setting up common scenarios for designing, analyzing, and optimizing processes in IT and software architectures [15]. It provides unique diagrams that allow specification of the activities, roles, tools and resources involved in the performance of an organization. These diagrams provide different types of abstractions that allow a deeper understanding of the organization as well as of the information management. These methods can be used as basis for the implementation of strategies like enterprise resource planning (ERP) [16], which seek to properly manage the internal processes of companies. Its implementation requires modeling of the processes conducted into the company, and several types of representations – depending on the type of business or process to be analyzed - may be required.

In summary, the traditional multi-abstraction techniques seek to provide multiple levels of details, and this dictates the amount of information contained in the model [17]. They provides different points of view for system analysis that can be based on the perspective of a particular role in life cycle stages [18], or on the analysis of "how", "when", "where" and "who" relates to the information or the process [14]. However, the above-mentioned modeling techniques are only focused on technological systems and/or in enterprise systems. CPSs are made up of combinations of technological, enterprise and natural systems. There can be some possibilities to integrate technological and enterprise systems when using modeling techniques such as UML and IDEF. However, techniques that integrate into the same representation natural systems are not available.

A CPS representation needed for conducting failure analysis requires the integration of natural systems as an integral and active component of the system. Such natural systems include living organisms as plants, animals and humans, who also routinely interact with other CPS components or subsystems. All these provide inputs and generate outputs that can also serve as inputs. As the entire system performance depends on the interconnections between the components of the multiple subsystems involved, the incorporation of perspectives of all underlying subsystems in one representation allows for identification of the influential factors of failure through the analysis of flows of energy, material and information.

In light of the above discussion and analysis, there is an apparent need to develop modeling techniques that integrate into the same representation scheme technological, enterprise and natural systems, which also allows multi-perspectives analysis that traditional modeling technics already supports. We explore this issue in the work presented in this paper. In the following Section, we introduce a dual-aspect modeling technique we developed as our attempt to come up with a solution to the challenges faced in modeling CPSs.

3. CONCEPT OF DUAL-ASPECT MODELING

The proposed model has been dubbed "dual-aspect model" because blends modeling knowledge from two different perspectives. Specifically, these perspectives relate to the manifestation of natural "organisms" and of a cyber-physical system or of a part thereof, which serves as augmentation. For instance, in the case of a transportation system, this can be a road infrastructure extended with advanced installation for traffic monitoring and control. The dual-aspect models facilitate the integration of the functions and the structural components of the two different systems and blending of the operational flows (material, energy and information) to achieve a synergetic behavior. This modeling concept relies on multiple abstractions that are captured in various layers of the dual-aspects modeling (DAM) scheme. There are four abstractions, namely: (i) objectives, (ii) functionality, (iii) structural management, and (iv) operational flows. Natural system can essentially be an implementation of physical, biological, social and/or engineering processes. In simple words, a natural system is a natural manifestation of "organisms". The objective of the Cyber-physical system is to provide added benefits through augmentation of the natural system. The dual-aspect model is developed gradually through the completion of each abstraction from both cyber-physical and natural perspectives (see Figure 1). This means that new details are added in each new abstraction layer, until the operational flows are completed. An abstraction in a given abstraction level incorporates in the same representation all the details specified after the completion of the models developed in the preceding abstraction levels. The proposed forms of abstraction are defined and explained in details in the following sub-sections.

3.1. Objectives abstraction

Objectives definition is the starting point of the dual-aspect modeling process. In this stage the main goals of the analysis should be defined. This definition is critical and important for modeling and representation of the system as well as for subsequent analysis of the system. Concrete performance, efficiency and/or operation-related objectives should be defined and elaborated. This would allow the imagined system to be analyzed and evaluated to determine, for instance its performance, factors influencing failure, or its likelihood of failure. The elicitation of objectives should be conducted through the formal process of system's requirements definition in the early development stage. These requirements will serve as the roadmap for conceptualization, modeling and representation of the system. The objectives should be defined from both natural and CPS perspectives. The objectives defined will underpin the definition of the functions of the system during functionality abstraction modeling.

3.2. Functionality abstraction

The functional abstraction layer describes the basic functions of the system from both natural and CPS perspectives. This abstraction allows understanding of which general functions are involved in the system operation. From the perspective of natural systems, it brings into the system the main natural functions, which can also include living actors such as humans or plants. And from the cyber-physical perspective, it brings into the system all the functions required for augmenting the natural system. During this modeling stage, the physical phenomena, which describe system operation, should be identified. These physical phenomena, along with the objectives formulated in the previous abstraction level as the basis for defining the main functions in cyber-physical augmentations, as well as in the associated natural systems are used as the basis for building functional abstraction model.

3.3. Structural abstraction

In order to identify and to itemize the main functions of the investigated systems, the structural abstraction layer is incorporated in the proposed dual-aspects modeling technique. It allows for the identification of new functions based on the analysis of the physical interrelationships of the constituent elements. Therefore, the structural abstraction describes the structural interrelations among the functional entities. It also defines the physical locations of entities. This representation is static in the sense that it only includes system's layout and architecture. No details of flows are specified. However, from the perspective of the natural system, physical components are also defined and their locations specified. From the cyber-physical augmentation perspective, the details of cyberware (info-ware) constituents (such as locations and the infrastructures required for the operation of the system) are also defined, but only from the viewpoints of physical presence.

3.4. Cyber-physical workflow abstraction

All the above-mentioned abstractions (both from the perspectives of natural and cyber-physical) are blended and summarized at the cyber-physical workflow abstraction layer. All functions involved in system operation, from the cyber-physical, as well as from the natural systems are integrated in this representation. This abstraction is based on the modeling technique proposed by Pahl and Beitz [7] in which flows of energy, information and materials

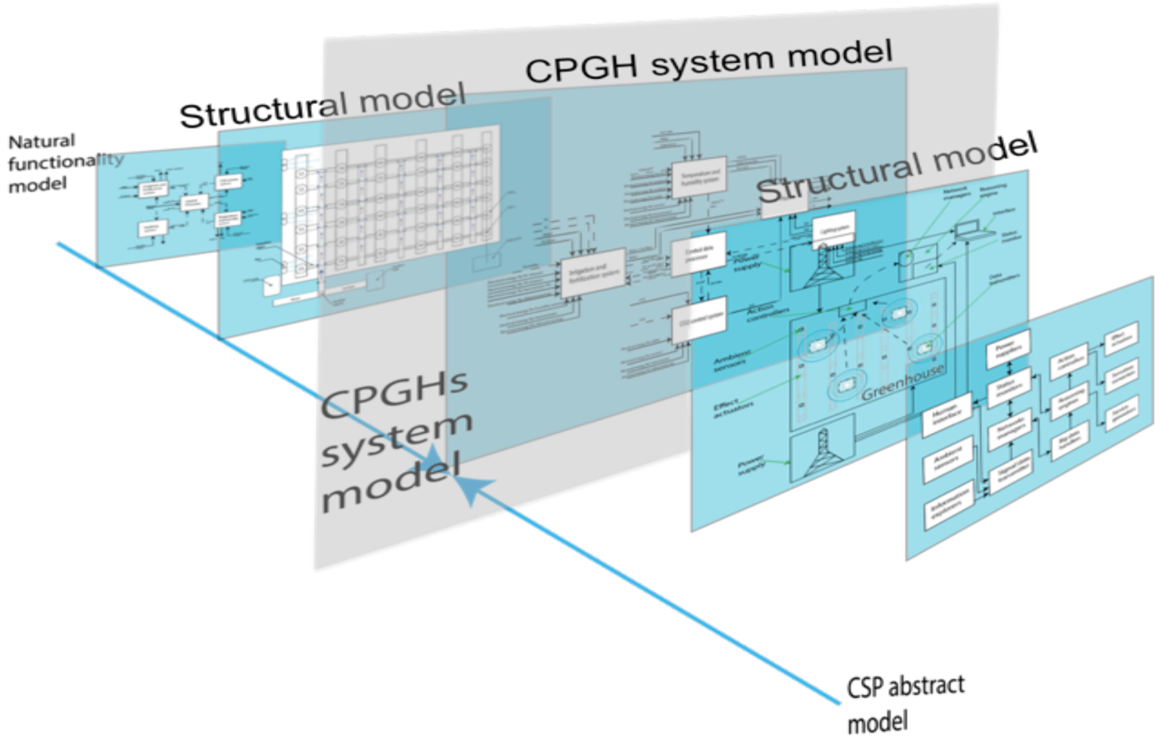

Figure 1 Dual-aspect model

are considered. This allows us to understand the operations of the system. The functions for both perspectives are connected through these flows and all transformation processes of both cyber-physical and natural systems are holistically represented. Due to systems complexity, a multilevel representation should be created to allow us to comprehensively represent and to understand the system and to provide different levels of details. The levels that should be considered in describing workflows are: (i) system level, (ii) sub-systems level, (iii) module level, (iv) units level, and (v) components levels.

System level

A system level cyber-physical workflow abstraction model represents the overall view of the system and allows us to understand the system's main functions as well as the general factors involved in its operation. A system level workflow abstraction model can be regarded as a black-box diagram and includes the main physical phenomena that are part of the system's performance.

Sub-system level

A sub-system level workflow model allows us to understand how the interactions among the sub-systems would be. This enables us to consider factors that influence the system (e.g., what come in and go out of each subsystem) and allows us to understand whether or not an output of the subsystem may become an input of another sub-system.

Module level

A module level workflow model can be considered as an act of zooming in or into a particular sub-system. This allows us to understand how the interactions among the modules that make up the system would be.

Units level

A unit level workflow model represents the interrelations among units and components. Components level is the lowest and most detailed abstract representation, as it allows us to represent and to understand how physical elements interrelates and how energy transforms, as well as the information flows among the main functional entities of the system. Each individual function, or cluster of functions may be represented as a singular particular abstraction.

The development of the proposed abstractions allows us to systematically incorporate into the final representation all the functions and flows involved in system operation. Separate analysis of the natural system's anticipated performance seeks to provide a good understanding of the effects and contributions of the natural elements to the system, with a view to provide a better integration of the subsystems. Better integration of subsystems would result into a more efficient and reliable performance of the entire CPS. The analysis of failures in CPSs is a post-process procedure of model definition. In this article we focus on the characteristic features that should be included in the model to make it useful for failure analysis. The proposed dual-aspect modeling process is based on the analysis of flows and dependencies between functions or components. One of the central requirements is that the modeling procedure should allow users to estimate the effects of flows (of information, energy or material) or functions suppression on the performance of systems operations, and allow identification of the factors that may cause or terminate flows and the number of components that may be affected by this. Work on this post-processing process is one of the subjects of the ongoing research and will be presented in our future publications.

In order to understand the proposed dual-aspect-modeling procedure, we present a case application example in the following Section. This particular case-study is focused on the implementation of the CPS concept in a greenhouse, which we refer to as Cyber-Physical Greenhouse (and abbreviate as CPGH) in this paper.

4. DEMONSTRATION OF THE APPLICABILITY OF THE DAM CONCEPT

In this Section, the proposed dual-aspects modelling (DAM) concept is used to model a cyber-physical greenhouse. The goal is to demonstrate and to show how the DAM concept can be used to create a practical cyber-physical system abstract model. The developed CPGH model will be used in our future research to analyze failures and to identify the factors that should be considered to avoid failures. As mentioned earlier, the application of the DAM concept involves conducting system analysis from both: i) natural system perspectives, i.e., the existing automated greenhouse, and from ii) the cyber-physical perspective (augmentations of the automated greenhouse with cyber-physical functions).

4.1. Natural system’s perspective

The natural system of this application case study is an automated greenhouse. A greenhouse seeks to provide proper or optimal conditions for crops to grow in an artificial environment by controlling several variables including for instance controlling temperature, CO2, irrigation and lights. To augment the functions of the greenhouse with cyber-physical functions, it should be fully analyzed and understood in the different abstraction levels. In the following subsections, we will show how to create the abstractions defined in the dual-aspect model (i.e., objective, functional and structural abstractions).

Greenhouse objective abstraction model

Greenhouse objectives should be stated by the client or owner of the greenhouse. Some of these objectives may be related to the expected availability of the system, its relationship with the expected quality of products, reduction of the likelihood of failures and so forth. The requirements that describe indicators of the availability of the system or costs of making the system available such as maintenance cost and probability of failure of the system or of its components can also be specified.

Greenhouse’s functional abstraction

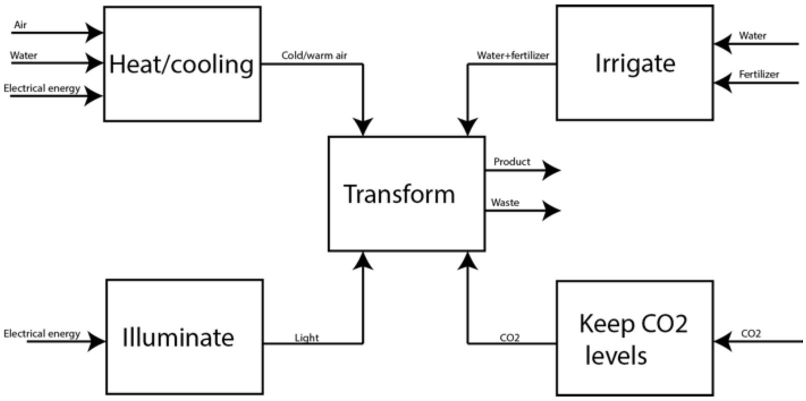

Figure 2 Greenhouse’s functional abstraction

After defining the greenhouse objectives, four main functions necessary for greenhouse operations were identified: i) heating/cooling, ii) irrigating and fertilization, iii) illuminating/lighting, and iv) keeping CO2 levels (see Figure 2). Heating or cooling involves controlling system temperature and humidity in the greenhouse; irrigating is essentially the process of providing the amount of water or moisture and fertilizer required for the plant’s growth;

illuminating or lighting allows system operations to proceed during the absence of sun light (e.g., during the night, or as an alternative to the use of sunlight should there be the need for this) which is required in natural processes such as photosynthesis; and keeping CO2 levels ensures that the desirable level of CO2 for the greenhouse processes is maintained. The accomplishment of these functions habitually involve interactions among various elements of the greenhouse, which may in turn affect the system performance or cause failures, and as a result contravene the defined objectives. These main functions were further analyzed at the next stage of greenhouses structural abstraction level, in which details of each function was provided in more specific ways, as explained below.

Greenhouse's structural abstraction

A layout of the current greenhouse was developed with the view to identify system operations (see Figure 3) and to provide the more detailed descriptions of the functions specified in the previous abstraction level of 'functional abstraction'. This layout shows the physical entities of the greenhouse system and their physical locations in the greenhouse, and the main functions as well as the function carriers. A function carrier can be components or units. Therefore, each function was decomposed. For instance, the cooling function was decomposed into (i) transmit, (ii) allow, (iii) transform, and (iv) unite functions. The 'transmit' function carrier refers to the process of transmitting electrical energy or power from an electrical source, e.g., to the fans; The 'allow' function carrier refers to the process of switching a system or a subsystem on/off e.g., to allow passage of power or energy for various purposes such as powering of the motors; the 'transform' function carrier deals with transformation of electrical energy into the movements; and the 'unite' function carrier involves taking in fresh air from the outside of the greenhouse and distribution of air inside of the greenhouse. The decomposition of the functions into sub-functions is the main output of this analysis. This decomposition is the input for the CPGH workflow abstraction. Theoretically, the bigger the decomposition is, the more detailed the analysis of interactions and failure becomes.

Since the 'system abstraction from the natural system perspective' should be blended with 'the system abstraction from the CPS perspective', similar abstractions should be developed from CPS perspective. The process of analyzing and developing system abstraction from CPS perspective is presented and discussed in the following Subsection.

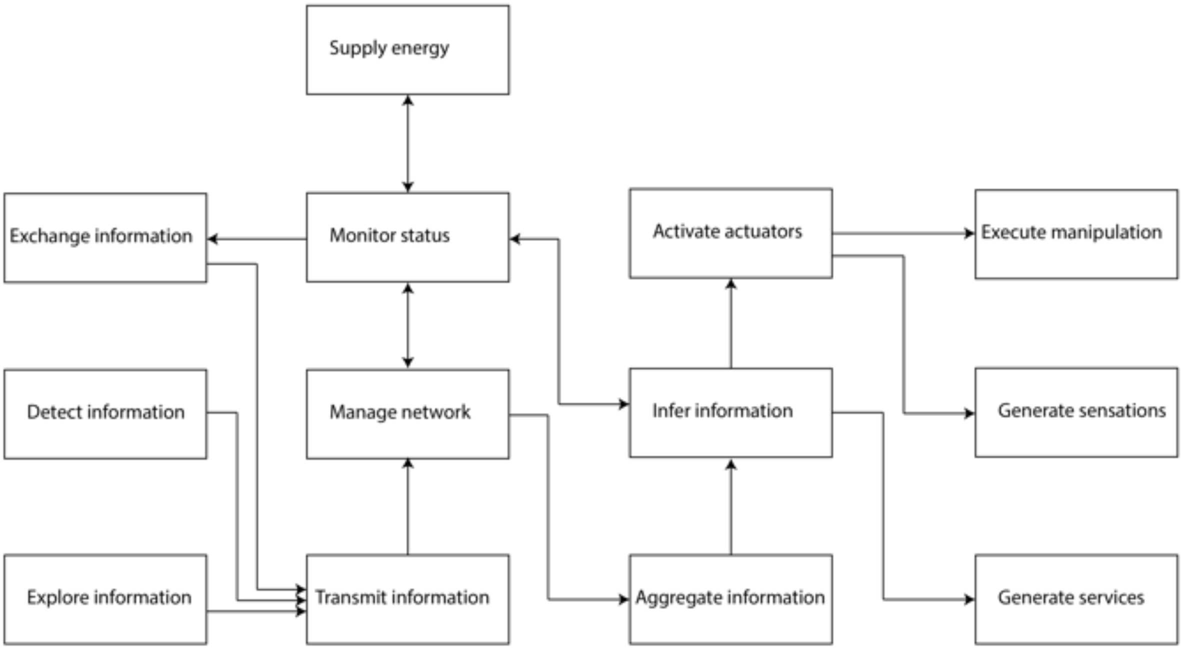

Figure 3 CPS's functional abstraction layer

4.2. CPS augmentation perspective

Knowledge of the objectives (or requirements), functions, structural layout, and (materials, energy and/or information) flows as well as the benefits and a good understanding of how a CPS will operate from CPS augmentation perspective is important in building a CPGH. Therefore, we analyzed the greenhouse at the DAM's four abstraction levels. As was in the case of the natural system perspective (refer to Section 4.1), we started by defining the objectives from CPS perspective, we then defined functions from CPS perspective at the functional abstraction layer and finally we formulated system's layout from CPS perspective at the structural abstraction level. After system analysis from CPS perspective was concluded, we subsequently blended the system description obtained from the analysis from natural system perspective with the system description obtained from the analysis from CPS perspective, and came up with a combined CPGH workflow model.

Objectives from CPS perspective

The main objectives of CPS implementation in automated greenhouses were defined at this stage. These objectives are summarized in the following general statements:

- To provide constant operations of sensing, transmission and processing of data and also to assure system's response.
- To avail data that can then be processed to generate knowledge.
- To improve failure related decision-making processes carried out based on available information – including, for instance, historical data of temperature, humidity, light intensity, CO2 concentration, power consumption, and soil moisture.

These objective statements were developed after carrying out needs analysis and formulating the requirements for the CPGH. As part of the continuous modeling process, these objectives were used as inputs in the process of defining functions at the functional abstraction level, as elaborated in the following Subsection.

Functional abstraction from CPS perspective

Based on the defined objectives, the main CPS

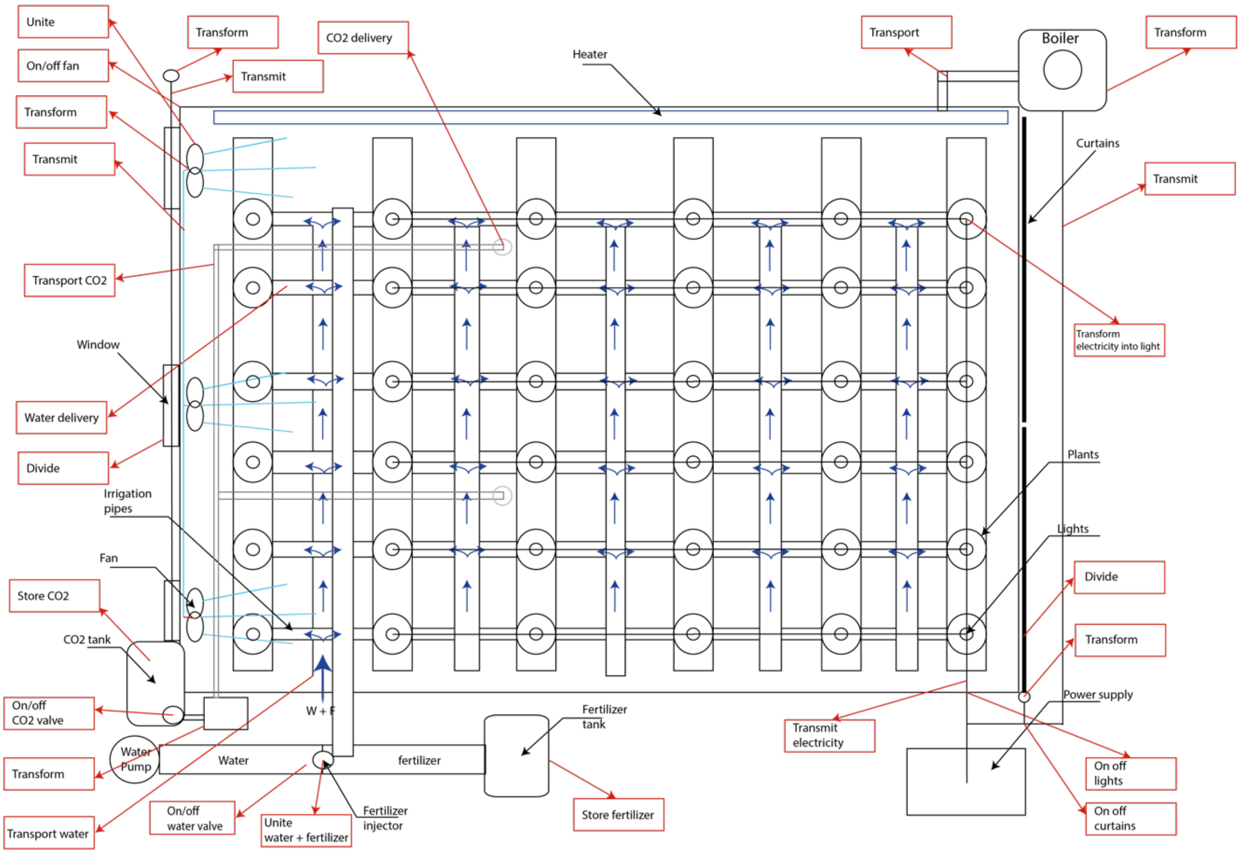

Figure 4 GH's structural abstraction

functions were defined (see Figure 4). The identified functions were i) exchange information, ii) detect information, iii) explore information, iv) transmit information, v) manage network, vi) monitor status, vii) supply energy, viii) infer information, ix) aggregate information, x) activate actuators, xi) execute manipulation, xii) generate sensations, and xiii) generate services. The exchange information function allows interaction between the user and the system. The detecting information function allows us to gather sensed signals that can be used to measure and evaluate the state of parameters. The exploring information function entails automated search of external information (internet or external databases) and using this information as input in performing other internal functions or processes in the system.

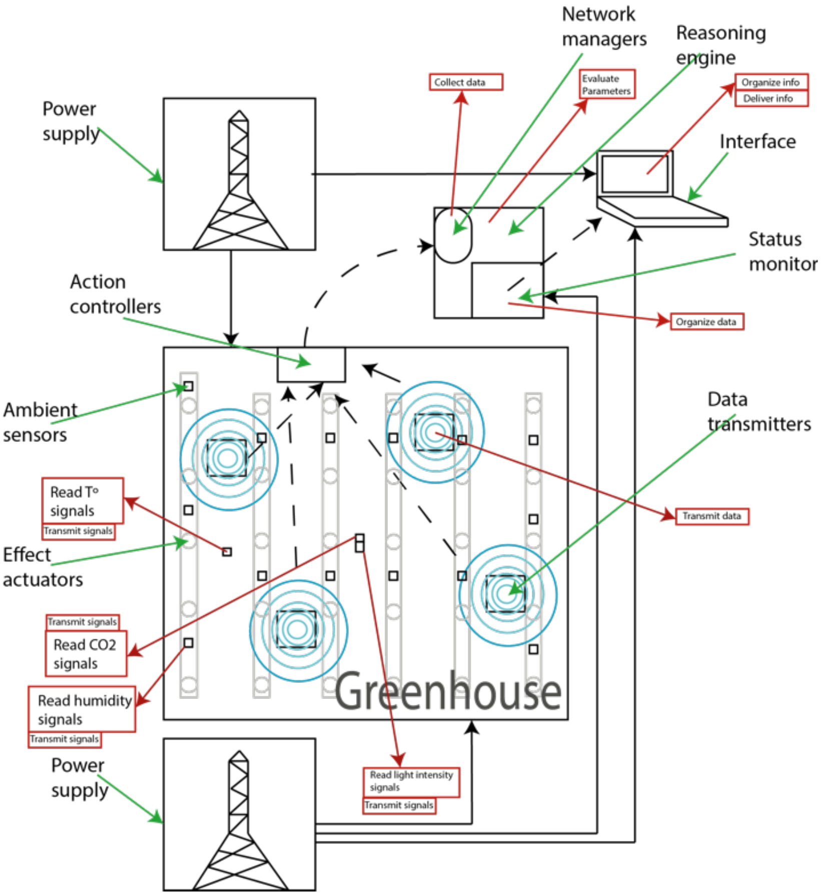

Figure 5 CPS's structural abstraction

The transmitting information function allows us to gather the information obtained (through sensing, exploration or user interaction) and sending this information to a central processor. The 'manage network' function manages networks and network based activities in order to achieve efficient and reliable performance. The 'monitor status' function allows the system to organize the data that is processed or stored. The 'supply energy' function allows the system to efficiently provide and manage the energy, material or the information required for the operation of the system. The 'infer information' performs calculation and makes decisions based on the available data. The 'aggregate information' function manages the information and in this way enables the system to operate efficiently. The 'activate actuators' function provides the signal required to enable the actuators to execute tasks. The 'execute manipulator' function allows the actuators in the system to execute actions. The 'generate sensations' function make use of physical devices to generate sensations in system's users, and the 'generate services' function make use of the knowledge available in the system to generate new functions, services and applications of the system. These functions were further decomposed at the abstraction level, as described in the following subsection.

Structural abstraction from CPS perspective

A layout of the functions of the greenhouse environment specified at the functional abstraction level was developed at this abstraction level. This layout allows us to make actual allocation of physical components of the system and to place cyber elements physically. The decomposition of CPS functions was carried out and the structural representation of the cyber-physical system created (see Figure 5). For instance, as can be seen, the 'explore information' function was decomposed into i) search info, ii) unite and evaluate parameters. The 'search info' sub function searches and explores the external information from databases as well as the information on the web. The process of searching for information can be carried out by using agents. The 'unite' sub function combines (and process) the information coming from various sensors with the external information, and uses this information for decision making. And the 'evaluate

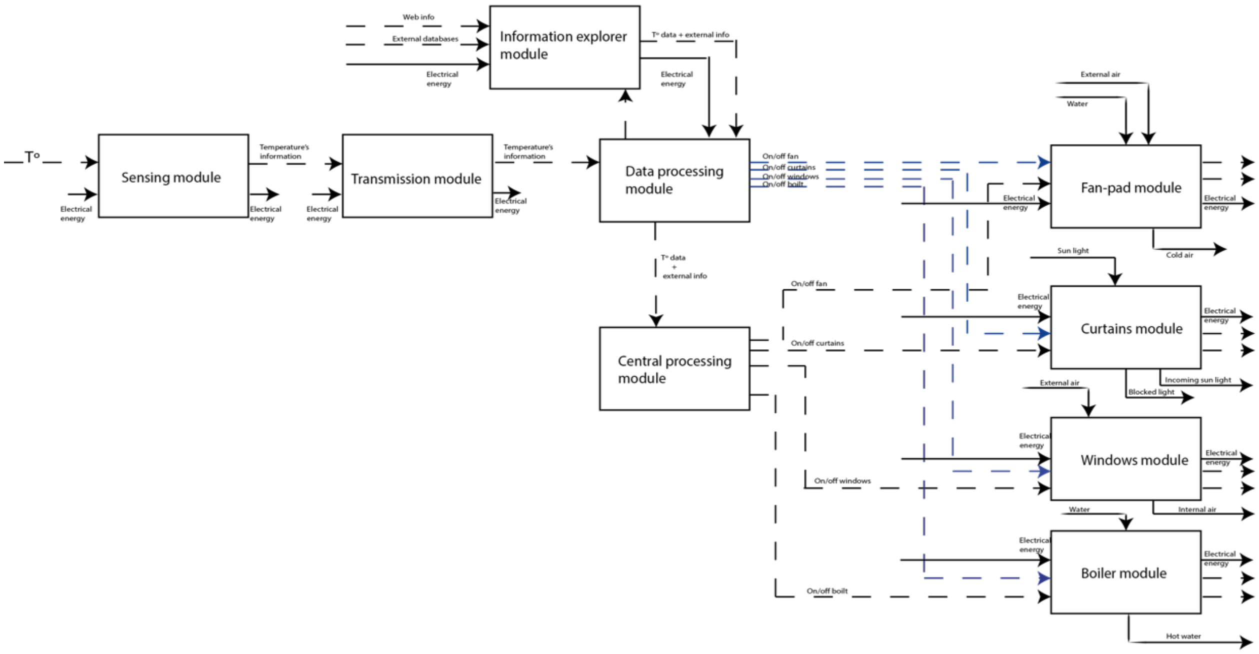

Figure 6 CPGH workflow: sub-system level

parameters' sub function determines the actions that would be carried out.

Once both analysis (from natural system's and CPS system's perspectives) have been carried out separately, the specified functions and their layouts can then be blended to form a CPGH workflow model, as explained in the following subsection.

CPGH workflow abstraction

Based on the analysis from both perspectives, the cyber-physical greenhouse workflow abstraction was created. The cyber-physical greenhouse workflow representation at each of the proposed levels (refer to Section 4.1) is shown in Figures 6 and 7 and discussed in the following paragraphs. Due to the complexity of the CPGH, only the temperature sub-system and the heating module is presented and discussed. A workflow abstraction is multiple levels in nature. As mentioned earlier, it allows the system to be represented at system level, at subsystem level, modules level and at units level. The CPCH workflow abstraction is therefore represented at these levels and discussed.

- **Level 1: System level**

The system level abstraction includes all subsystems that make up the system, and show their interaction and flows of information, energy and material. Therefore, based on the functions defined at the greenhouse functional abstraction level, temperature and humidity, irrigation and fertilization, CO2 control, and lighting sub-systems were included in the analysis, as shown in Figure 6. Plant was also considered as a sub-system, since the outputs of the other sub systems affect the plant, and the plant's outputs may also be an input of other sub systems.

- **Level 2: subsystem's level**

We further zoomed into each of the sub-systems, to understand the interactions among the modules that made-up each particular sub-system. For demonstration purposes, only the temperature and humidity sub-system are discussed in this article (see Figure 7). In this abstraction level, the main

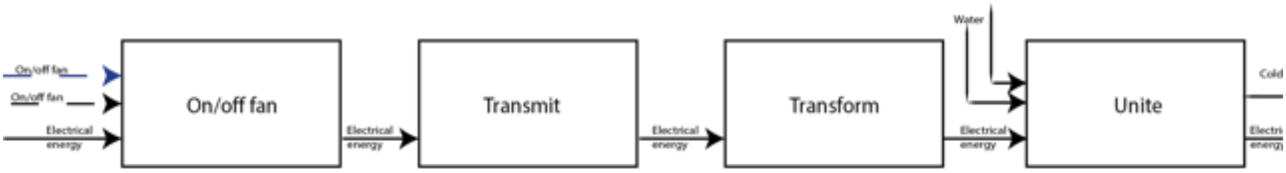

Figure 7 CPGH module: Fan/pad module

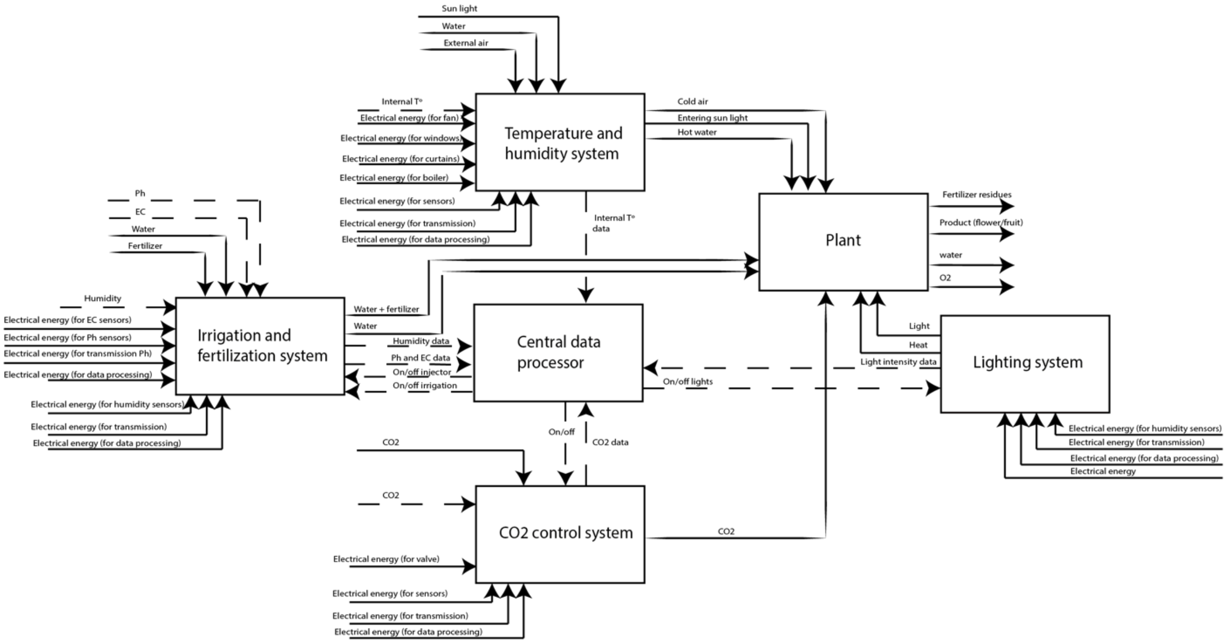

Figure 8 CPGH workflow: system level

functions described in the functional and structural abstraction levels both from CPS perspective and natural greenhouse perspective were included as the modules. From CPS perspective: i) sensing module, ii) transmission module, ii) information explorer module, iv) data processing module, v) central processing module were identified. Fan-pad, curtains, windows and boiler module were taken from the structural abstraction layer of the natural greenhouse to create the heating/cooling function of the temperature and humidity system.

- **Level 3: Module level**

We also zoomed-in into each module to understand

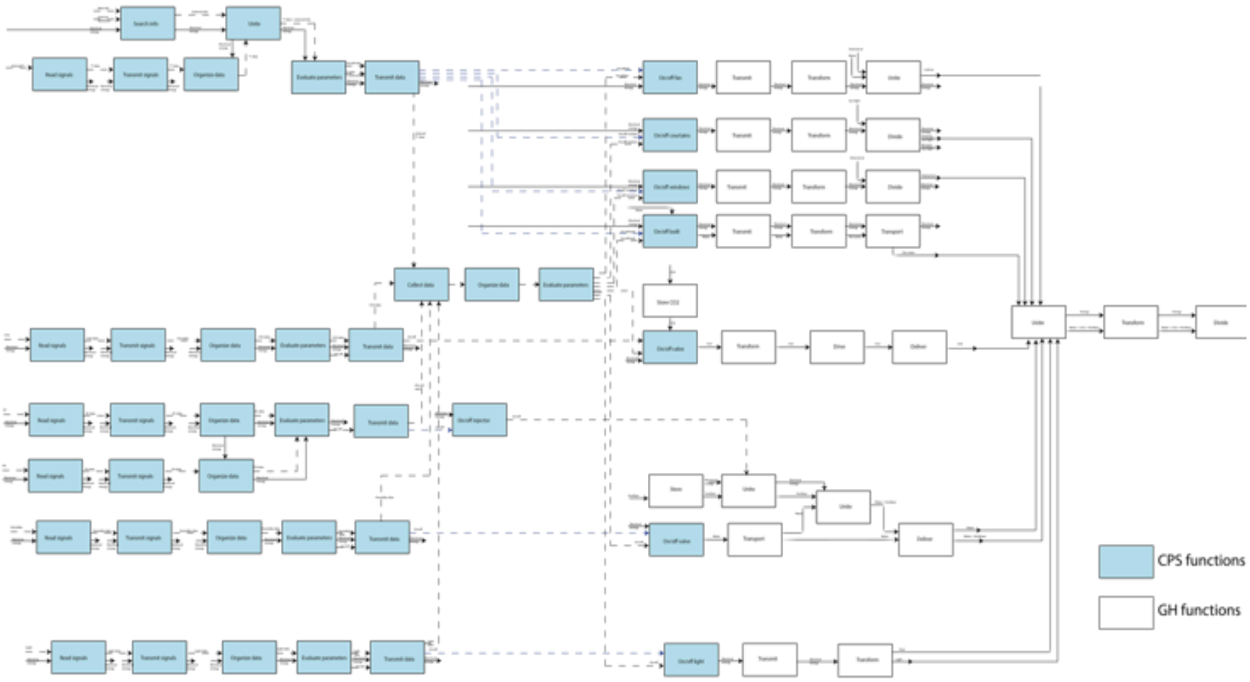

Figure 9 CPGH workflow: general view of the module's level

the interactions among units and components. In this particular case, no units were identified. Thus, each module only consisted of the functions that describe components. As an example, the fan/pad module (Figure 8) and the information explorer module are presented. In fan/pad module, the function that activates the actuator is implemented as an On/Off fan switch. In this setting, the information coming from the central processor is required, as well as the electric energy. Electric energy is transmitted to each of the fan's engine, where it is transformed into movement, and finally, air is moistened in the pad, by using the 'unite' function. 'Functions transmit', 'transform' and 'unite' are taken from the greenhouse's structural abstraction, while On/Off fan is taken from CPS's structural abstraction. A general view of the whole system's module representation is shown in Figure 9. It shows the combination of the functions taken from the analyses carried out from both the CPS perspective and greenhouse perspective. The functions highlighted in blue in Figure 9 originated from CPS perspective analysis while those in white background originated from the natural greenhouse perspective.

The levels of detail achieved through abstraction allow us to use the model for failure analysis in various ways. These abstractions makes it possible to represent components by using one or more functions and enables us to understand the internal processes that that should be in order to accomplish the tasks. They provide a global view of the components that make up the CPS as well as their interactions. They therefore allow us, for instance, to determine what would happen if any of the functions of a particular component is not conducted. This makes them suitable for use in qualitative analysis e.g., to determine the influential factors of failure in CPSs. Work on development of a method for determination of the influencing factors is still going on.

5. IMPLEMENTATION ISSUES

There two types of failure analyses can be performed by using the proposed DAM technique. One kind of analysis is qualitative failure analysis in which the influences of particular components of the system on other components can be analyzed, and the most critical components for system operations can be identified. To this end, qualitative failure analysis can be conducted in several ways, for instance, by applying the graph theory [19] in which functions can be nodes and the flows can be the links between nodes. Furthermore, the knowledge that system modeling provides can be used as input, for instance, in performing failure mode effect analysis (FMEA) [20] or fault tree analysis (FTA) [21].

Another kind of analysis is quantitative failure analysis. It should be noted here that performing quantitative failure analysis requires the identification of the mathematical equations that describe system functions. These mathematical equations should then be transformed into active models in order to perform simulations, for instance in multi-domain simulation environments such as Simulink. Such a quantitative analysis can be conducted to forecast failure through implementation of timed modules of computation based on differential equations. In both cases the failure analysis is conducted as a post-process of model development in which the knowledge obtained through the model development is very important. Work on studying the application of DAM technique for analyzing failure is still going on and the results will be presented in our future publications.

6. SUMMARY AND CONCLUSIONS

We have argued in this article that analysis of failures in CPSs requires new modeling techniques. Currently available techniques focus more on technical and enterprise systems. Some of the key elements of CPSs such as natural systems are not considered. Furthermore, since CPSs offer new services through the cyber-physical augmentation of natural systems, we pointed out that this relationship makes it necessary to model and analyze natural systems as another important constituent of the system and as a possible cause of failures. We also have argued that a good understanding of CPS behavior can contribute to the improvement of system availability, and help to increase system reliability. This can also allow us to forecast and reduce failures or eliminate events that adversely affect the operation or functioning of the system.

We carried out a literature review and found that techniques that integrate into the same representation natural systems are not available. We subsequently proposed a dual-aspect modeling technique and illustrated its applicability by using a CPGH application as a case-study. The proposed dual-aspect modeling technique provides a means for qualitative analysis. This analysis takes into account the interactions between the elements involved in system operation. These interactions, which may include external factors that are within the operational scope of the CPS, influences the system operation and allows determination of the influential factors of failure of CPS. Interactions are represented by specifying the flows of material, energy and information and are based on physical phenomena. Since the analysis is based on functions, which require inputs that are transformed into outputs, this modeling technique can also be used for quantitative analysis. To this end, each function is expressed by using a mathematical expression that describes the behaviors of the physical phenomena represented by the function. These quantitative analyses allow us to forecast future system operation and failures. However, there is still a need for a good understanding of modeling of CPS and natural systems.

The work presented in this paper is part of a large ongoing research project and we have only focused on the development of the model, as the first step of the research on analysis of failure in CPSs. Future work include identification of the factors that influence failure in CPS based on the information available at the design stage. In this case, we expect that the flows and functions will contribute to determination of how the operation of the system can be affected and will also provide inputs for performing thorough analyses such as failure mode effect analysis or fault tree analysis. The application case study presented in this paper include a simplified depiction of a standard CPGH intended only for explaining the new concepts introduced in this paper. It still need to be reviewed and validated e.g., by involving by experts. The following stages of the research will also focus on refining the proposed modeling technique and on identification of the factors that influences failure. Furthermore, quantitative analysis procedures will be incorporated into the proposed modeling technique.

REFERENCES

[1] S. Strecker, D. Heise, and U. Frank, “RiskM: A multi-perspective modeling method for IT risk assessment,” *Inf. Syst. Front.*, vol. 13, no. 4, pp. 595–611, Sep. 2011.

[2] M. Heß, “Towards a Domain-Specific Method for Multi-Perspective Hospital Modelling – Motivation and Requirements,” in *Design Science at the Intersection of Physical and Virtual Design*, J. vom Brocke, R. Hekkala, S. Ram, and M. Rossi, Eds. Springer Berlin Heidelberg, 2013, pp. 369–385.

[3] M. Rabe, R. Jochem, and H. Weinaug, “Multi-perspective Modelling of Sustainability Aspects within the Industrial Environment and their Implication on the Simulation Technique,” in *Advances in Sustainable Manufacturing*, G. Seliger, M. M. K. Khraisheh, and I. S. Jawahir, Eds. Springer Berlin Heidelberg, 2011, pp. 315–320.

[4] A. Goldstein and U. Frank, “A Language for Multi-Perspective Modelling of IT Security: Objectives and Analysis of Requirements,” in *Business Process Management Workshops*, M. L. Rosa and P. Soffer, Eds. Springer Berlin Heidelberg, 2013, pp. 636–648.

[5] M. La Rosa, M. Dumas, A. H. M. ter Hofstede, and J. Mendling, “Configurable multi-perspective business process models,” *Inf. Syst.*, vol. 36, no. 2, pp. 313–340, Apr. 2011.

[6] E. A. Lee, “CPS foundations,” in *Proceedings of the 47th Design Automation Conference*, New York, NY, USA, 2010, pp. 737–742.

[7] G. Pahl, W. Beitz, J. Feldhusen, and K.-H. Grote, “Fundamentals,” in *Engineering Design*, Springer London, 2007, pp. 27–62.

[8] D. R. Ferreira, “Evolution of Enterprise Systems,” in *Enterprise Systems Integration*, Springer Berlin Heidelberg, 2013, pp. 3–14.

[9] B. Nuseibeh, A. Finkelstein, and J. Kramer, “Method engineering for multi-perspective software development,” *Inf. Softw. Technol.*, vol. 38, no. 4, pp. 267–274, 1996.

[10] U. Frank, “Multi-perspective enterprise modeling (MEMO) conceptual framework and modeling languages,” in *Proceedings of the 35th Annual Hawaii International Conference on System Sciences, 2002. HICSS*, 2002, pp. 1258–1267.

[11] "Introduction to the Unified Modeling Language (UML)", in *Guide to Applying the UML*, Springer New York, 2002, pp. 1–11.

[12] J. Bézivin and P.-A. Muller, “UML: The Birth and Rise of a Standard Modeling Notation,” in *The Unified Modeling Language. «UML»’98: Beyond the Notation*, J. Bézivin and P.-A. Muller, Eds. Springer Berlin Heidelberg, 1999, pp. 1–8.

[13] C. Menzel and R. J. Mayer, “The IDEF Family of Languages,” in *Handbook on Architectures of Information Systems*, A. P. D. P. Bernus, P. D. K. Mertins, and P. D. G. Schmidt, Eds. Springer Berlin Heidelberg, 2006, pp. 215–249.

[14] J. Kingston and A. Macintosh, “Knowledge management through multi-perspective modelling: representing and distributing organizational memory,” *Knowl.-Based Syst.*, vol. 13, no. 2–3, pp. 121–131, Apr. 2000.

[15] R. Davis and E. Brabänder, “Introduction to the ARIS Platform,” in *ARIS Design Platform*, Springer London, 2007, pp. 13–25.

[16] A. Shtub, “Organizations and Organizational Structures,” in *Enterprise Resource Planning (ERP): The Dynamics of Operations Management*, Springer US, 1999, pp. 18–31.

[17] P. Benjamin, M. Erraguntla, D. Delen, and R. Mayer, “Simulation Modeling at Multiple Levels of Abstraction,” in *Proceedings of the 30th Conference on Winter Simulation*, Los Alamitos, CA, USA, 1998, pp. 391–398.

[18] M. A. Jeusfeld, M. Jarke, H. W. Nissen, and M. Staudt, “ConceptBase: Managing Conceptual Models about Information Systems,” in *Handbook on Architectures of Information Systems*, A. P. D. P. Bernus, P. D. K. Mertins, and P. D. G. Schmidt, Eds. Springer Berlin Heidelberg, 2006, pp. 273–294.

[19] G. O’Regan, “Graph Theory,” in *Mathematics in Computing*, Springer London, 2013, pp. 267–275.

[20] M. Ben-Daya, “Failure Mode and Effect Analysis,” in *Handbook of Maintenance Management and Engineering*, M. Ben-Daya, S. O. Duffuaa, A. Raouf, J. Knezevic, and D. Ait-Kadi, Eds. Springer London, 2009, pp. 75–90.

[21] M. Čepin, “Fault Tree Analysis,” in *Assessment of Power System Reliability*, Springer London, 2011, pp. 61–87.