Modelling Work Domain Knowledge with the Combined Use of Abstraction Hierarchy and Living Systems Theory

Abstract

This study is aimed at developing a new method for modelling work domain knowledge with the combined use of abstraction hierarchy (AH) and living systems theory (LST). AH has been widely used as a work domain knowledge representation framework in the field of cognitive systems engineering and human-computer interaction, and its usefulness has been proved in a range of work domains. However, its effective use still remains a challenging issue. In order to address this problem, this study firstly points out several issues that can be raised in the use of AH and then explains why and how LST can give concepts and principles helpful to resolve them. The proposed method offers a framework for how to combine AH and LST, particularly to identify functional knowledge at higher abstraction levels. It also offers a process for modelling the knowledge of a work domain based on the combined use of AH and LST. The use of the proposed method is exemplified by modelling the knowledge of a simplified secondary cooling system of nuclear power plants. The proposed method is a new approach to refining the concepts of AH and modelling the knowledge of a work domain that humans should interact. It is believed that it will be a useful tool for knowledge modellers in identifying and modelling the knowledge of a work domain in terms of its functional structure. However, it should be noted that its usefulness can be limited to technology-oriented engineering systems; it would not be easily applied to human activity-oriented systems.

Keywords: Knowledge modelling; Knowledge representation; Work domain analysis; Abstraction hierarchy; Living systems theory

1. Introduction

The nature of human operators' tasks in complex socio-technical systems, such as nuclear power plants (NPPs) and advanced manufacturing systems, is becoming increasingly cognitive and knowledge-intensive (Hollnagel and Woods 2005). Typical cognitive tasks in these systems include monitoring, situation assessment, decision-making, diagnosis and so on (Schraagen et al. 2000). Several types of computer-based systems for supporting such a cognitive task can be developed. Knowledge modelling is a fundamental activity in the design and management of computer-based systems for supporting human cognitive tasks in complex socio-technical systems (Becerra-Fernandez et al. 2004; Coffey and Hoffman 2003). However, it is considered difficult to identify knowledge that human operators should understand and to represent it in a form that is compatible with human operators' cognitive process (Vicente 2001).

To conduct cognitive tasks, human operators need to understand and manage several types of knowledge (Ham et al. 2011), which include work domain knowledge, task knowledge, strategic knowledge, organizational knowledge, situation knowledge, etc. Of those, a correct understanding of work domain knowledge is significant to the efficient and effective operation of complex socio-technical systems (Rasmussen 1986). For example, human operators of NPPs should have a correct understanding about how a plant works in order to generate electricity by the use of nuclear fuel.

This study deals with the problem of analysing and representing work domain knowledge. Although various approaches have been effectively used for modelling work domain knowledge, abstraction hierarchy (AH) developed in the community of cognitive systems engineering has been regarded as the most theoretically advanced framework (Rasmussen et al. 1994; Vicente 1999b). Its usefulness has been demonstrated in a range of application studies; however, its effective and systematic use still remains as a research problem (Naikar et al. 2005). In order to address this research problem, this paper proposes a new method for modelling work domain knowledge that incorporates the concepts and principles of living systems theory (LST) into AH. It aims to help model work domain knowledge based on AH more systematically and comprehensively.

The remainder of this paper is organized as follows. First, we review three research backgrounds, which are the concept of work domain knowledge and its meaning to human cognitive works, the concept of AH and its applications, and LST and its applications. Then we propose a new approach to modelling work domain knowledge, which combines the use of AH and LST. We explain the conceptual framework for the proposed approach and the practical process of using it. To demonstrate the usefulness of the proposed approach, we apply it to the problem of modelling the knowledge of a simplified secondary system of nuclear power plants (NPPs). Lastly, we conclude this paper by suggesting future research directions to improve the proposed approach.

2. Research background

2.1 Work domain knowledge and human works

Figure 1 shows a general model of human-systems interaction (HSI) and the concept of work domain in complex socio-technical systems such as NPPs. In these systems, human operators should interact with a work domain through a computer-based user interface (UI) (Hollnagel and Woods 2005). Work domain can be defined as the system being controlled, independent of any worker, automation, event, task, or device (Vicente 1999a). The nature of interaction between human operators and a work domain is a cognitive task. Human operators perform several types of cognitive tasks, such as situation assessment, planning, and diagnosis, in order to monitor, control, and supervise a work domain. Thus the performance of these systems is much dependent on the cognitive performance of human operators.

<Figure 1. General model of HSI and the concept of work domain>

Human operators need to understand and use several types of knowledge in order to perform their cognitive interaction with a work domain (Wiig 2003; 2004). The types of knowledge that human operators need to know can be identified from the studies of human mental models and cognitive tasks analysis. Many studies on mental models claim that there are five types of knowledge in a mental model: work domain knowledge, task knowledge, strategy knowledge, collaboration knowledge, and interface knowledge (Jonassen and Hung 2006; Rouse and Morris 1986; Staggers and Norcio 1993). Studies on cognitive task analysis also support these distinctive knowledge types (Hoffman and Militello 2009; Vicente 1999a).

Work domain knowledge refers to knowledge about how a work domain is designed and operated in terms of function, behaviour, and structure. Work domain knowledge represents the actually designed knowledge of a work domain; thus it can be said that work domain knowledge is highly related to declarative or principle knowledge (Ham and Yoon 2007; Little 2009). For example, the work domain knowledge of a NPP represents all the functions designed to generate electricity and maintain its safety, the interrelationships of those functions, the components and devices designed to realize those functions, the behaviours and possible states of those components and devices, and so on.

Task knowledge means knowledge about how a task can be conducted. For example, one of human operators' tasks in a NPP is to test a mechanical component comprising a plant system. For this task, they need to plan the testing activities, which determines what kinds of operations should be conducted and in what order they should be carried out. Most of the task knowledge can be represented as a procedure; thus it can be said that task knowledge is highly related to procedural knowledge (Vicente 1999b). However, a task can be achieved in various ways. A strategy can be defined as a more detailed way to achieve a task. Strategy knowledge refers to knowledge on how to conduct a strategy (Meso et al. 2002). In a complex socio-technical system, a task is usually conducted by a team consisting of human operators and automation, rather than a single human operator. In this case, team members should understand how they should collaborate to conduct a task, which includes what roles they should play and how they communicate each other. Such knowledge is represented as collaboration knowledge. As stated above, human operators interact with a work domain through computer-based user interfaces, such as information displays. It is essential for human operators to understand the design features of user interfaces to conduct their tasks. Interface knowledge refers to knowledge on the design features of user interfaces that human operators use.

There is no doubt that human operators need to possess and use all types of knowledge in order to conduct their tasks in a system. However, a lot of studies on human performance in complex socio-technical systems claim that the importance of work domain knowledge is second to none (Hollnagel and Woods 2005; Kilgore et al. 2009; Lind 1994; Rasmussen 1986; Vicente 2001). Understanding design principles underlying a work domain is a prerequisite to the study and use of other types of knowledge, particularly in a safety-critical system (Vicente 1999a; Burns et al. 2004).

Several approaches to work domain knowledge modelling have been developed. Some examples include function flow block diagram in the field of systems engineering (Kossiakoff and Sweet 2002), function-behaviour-structure (FBS) framework in the field of design theory (Gero 1990; Gero and Kannengiesser 2004), production rule and semantic network in the field of artificial intelligence (Rich and Knight 1991), and unified modelling language (UML) in the field of software engineering (Fowler 2004). Several cognitive task analysis methods have been also developed to model work domain knowledge (Burns and Vicente 2001; Diaper and Stanton 2004; Schraagen et al. 2000). Although these methods have been useful for work domain knowledge modelling, their limitations can be identified by the three criteria suggested by Vicente (1999b).

Vicente (1999b) stated that three criteria can be used to compare various forms of work domain modelling methods: device-independence, event-independence, and psychological relevance. Device-independence means that to what extent a modelling method is independent of the characteristics of the existing device used to perform the work, and the current work practices induced by the device. Event-independence means that to what extent a modelling method can be used independently of a particular class of pre-defined events or situations. Psychological relevance means that to what extent a modelling method results in a representation that is psychologically plausible (compatible with users' thinking processes).

Among work domain knowledge modelling methods developed so far, including those methods described above, it is rare to find a modelling method that satisfies all the three criteria. For example, function flow block diagram can be used for any device; however, it is used based on specific events and not psychologically relevant. UML can be used for any event situations in any device; however, it is difficult to say that it is psychologically relevant. Many studies demonstrated that AH meets all the three criteria (Bisantz and Vicente 1994; Bisantz and Mazaeva 2009; Rasmussen 1986; Vicente 1999b). For this reason, AH has been regarded as one of the most theoretically advanced method for analysing and modelling work domain knowledge.

2.2 Abstraction hierarchy (AH)

AH is a multi-level knowledge representation framework for describing the functional structure of a work domain. It was originally developed to represent the design knowledge of a complex process control system in the field of cognitive systems engineering. However, as explained later, it has been effectively used for representing several other types of work domains (Bisantz and Burns 2009; Burns and Hajdukiewicz 2004; Jenkins et al. 2008; Vicente 2002).

Theoretically, there can be any number of abstraction levels of an AH model; there is no absolute answer to the number of abstraction levels of the AH model. However, several studies showed that five abstraction levels are effective and meaningful for modelling most of the complex socio-technical systems (Naikar et al. 2005; Vicente 1999a). From the top level, the five abstraction levels are: functional purpose (FP), abstract function (AF), generalized function (GF), physical function (PF), and physical form (P) (Rasmussen et al. 1994). Table 1 explains the general meaning of each abstraction level, and Table 2 gives three examples of AH- based work domain knowledge modelling.

<Table 1. Meaning of five abstraction levels in the AH>

<Table 2. Examples of AH-based work domain knowledge modelling (Rasmussen (1986))>

FP represents the ultimate functions that a work domain should fulfil or the constraints that should be considered in the interaction between a work domain and its surrounding environment. The intended functions of a work domain against its environment should be explicitly represented at this level.

A set of more concrete functions should be implemented to realize the ultimate functions identified at the FP-level. They are usually represented at the GF-level and sometimes called as purpose-related functions. It should be noted that GF-level functions are independent of their physical implementations or processes. For example, in Table 2, one of the GF-level functions of washing machine is heating, which is absolutely needed to realize the FP-level functions. However, heating can be physically implemented in various ways, such as electrically or mechanically, which are generally represented at the PF-level. Thus more abstract, generalized functions should be represented at the GF-level.

AF describes how and in what priority GF-level functions work together to realize FP-level functions. Additionally, AF offers a set of criteria that can be used to judge how well GF-level functions implement FP-level functions. For this, AF-level functions are generally represented in terms of the flow of mass, information, energy, money, and so on.

As explained above, PF represents how GF-level functions are implemented more concretely or physically. PF describes physically implemented functions (e.g., electrical, mechanical, and chemical functions) that can be identified from the physical states of a component or physical objects. For example, in the case of washing machine, heating function at the GF-level can be implemented in two ways: (1) electronic heating on the surface of drum or (2) mechanical heating by the use of hot vapour. These two physically implemented heating functions are modelled at the PF level.

Actually visible appearance and form of components and devices designed in a work domain are represented at the P-level. For example, in the case of washing machine, the size and weight of pumps and valves, the layout of components, and the shape of drum are represented at the P level.

There are three points to note when using AH for work domain knowledge analysis. One important characteristic of an AH model is that it is defined by many-to-many structural goal-means relationships between adjacent levels (Rasmussen 1985). In other words, when there is a particular function at one level, its higher level explains the reasons why the function is designed, whereas its lower level illustrates how the function is actually implemented. In the abstraction levels of an AH model, higher levels contain the information about the functional purpose of a work domain and lower levels describe the information about the physical implementations of its functions (Rasmussen 1986).

Secondly, the concept of AH is conceptually differentiated from the concept of part-whole physical decomposition that is commonly used in a traditional system modelling. The part-whole physical decomposition of a system is concerned with the hierarchical levels of a system that can be classified in terms of its physical structure or granularity. As in the AH model, there can be any number of hierarchical levels in the part-whole decomposition. However, it seems to be sufficient to use five levels: a whole system, subsystems, functional units, subassemblies, and components, which ranges from the coarsest level of a system (a whole system) to its finest level (components). A whole system is composed of several subsystems, and a subsystem is made up of several functional units, and so on. The relationship between two adjacent levels in the part-whole decomposition is 'part-of' and 'whole-of'. For example, if a subsystem is linked to several functional units, it means that all the functional units are parts of the subsystem and the subsystem is the whole of all the functional units. This relationship is clearly distinct from the 'structural goal-means relationships' specified in the AH model. Let's suppose that a current goal is the moving of two persons from A to B. Two structural means for achieving this goal can be an automobile and a bus. However, an automobile is not part of the goal 'moving two persons'.

Although the AH levels and the part-whole decomposition levels are conceptually orthogonal, they are actually highly coupled. Thus the FP-level of AH is usually identified at the whole systems level, and the P-level of AH are generally found at the component level. Most of the other three levels (AF, GF, and PF) of AH are identified between the whole system and the component levels. Figure 2 shows a matrix to represent the knowledge of a work domain, which is composed of two dimensions: functional abstraction levels and part-whole decomposition levels. This matrix makes it easier to represent how top-level functional purposes of a work domain are implemented into visible physical objects.

<Figure 2. Abstraction-Decomposition space for a work domain>

Thirdly, it should be noted that different abstraction levels do not describe different systems but a single, same system from a different perspective. However, the higher levels of AH generally describe the reasons why the designed functions exist for normal working of a system. In contrast, because the lower levels of AH can be regarded as means for realizing their higher-level functions, they describe the causes for abnormal working states of a system.

AH has been used in a range of work domains, particularly in safety-critical complex socio-technical systems. Additionally, its modelling representation has been used for several purposes, including the design of user interfaces and training systems, the analysis of accidents and incidents, and the evaluation of design proposals. Table 3 summarizes the work domains where AH has been used or the application problems for which AH-based representation has been used.

<Table 3. Work domains or application problems using the AH>

2.3 Living systems theory (LST)

Living systems theory (LST) aims to offer the general principles and concepts for explaining the structure, interaction, behaviour and development of all living systems (Bailey 2006). As a unified theory, LST integrates the general systems concepts and principles that can be found across a range of disciplines including biology, physiology, sociology, economics and management. In LST, a living system is defined as a physical phenomenon existing in space and time (Miller 1978). It is an open self-organizing living thing that interacts with its environment.

In order to survive over time, living systems should be maintained by flows of matter, energy, and information. They must be able to do the following high-level functions: material processing, energy processing, information processing, synthesis of parts by combining materials, rearrangement and connection of disarranged parts, energy storing for fuel reserves and necessary structure, removal of worn parts, and so on (Skyttner 2005). Living systems have several essential subsystems responsible of specific basic functions needed for performing the high-level functions described above.

LST defines 20 critical subsystems that process the flows of matter, energy, and information. These subsystems achieve basic functions essential for the survival of living systems. However, they can be categorized into three groups: two subsystems processing matter, energy, and information, eight subsystems processing only matter and energy, and ten subsystems processing only information. With these 20 critical subsystems, LST offers theoretical foundations for building a domain-independent functional ontology (Cowan et al. 2006). Table 4 explains the functions conducted by the 20 essential subsystems. LST also offers the symbolic representation scheme for the 20 subsystems; however, it will not be described here as it is not relevant to the topic of this study.

<Table 4. Categorized subsystems of LST>

LST deals with the nature of hierarchical structure of living systems. The 20 essential subsystems and characteristics of living systems can be found in several types of living systems, which can be as simple as a single cell or as complex as a complex organization like United Nation. LST categorizes living systems into eight hierarchical levels. A higher-level living system contains the next lower-level one in a nested way. The eight hierarchical levels specified by LST include: cells, organs, organisms, groups, organizations, communities, societies, and supranational systems (Kalaidjieva and Swanson 2004).

Cowan et al. (2006) stated that LST as a general systems theory is also applicable to nonliving entities, such as engineering systems, because there are analogies between living and nonliving systems in terms of functions needed for achieving their purposes. Those functions and their interactions are well explained by the use of the 20 essential subsystems defined by LST. For this reason, LST can be a useful tool for system designers, enabling both functional knowledge representation of a system and system partitioning in a hierarchical manner (Koch et al. 1995). It has been demonstrated in a range of work domains that LST can be effectively used for identifying and modelling functional requirements of a system early in its design (Hirtz et al. 2002; Letsu-Dake and Ntuen 2009; Louderback and Merker 2006).

2.4 Research Motivation

As described previously, the AH has useful features for supplementing the drawbacks of other work domain knowledge modelling methods, and its usefulness has been demonstrated in a range of work domains. Thus work domain analysis based on AH has been increasing. However, the correct understanding of AH and its effective uses still remain difficult for researchers and practitioners (Jenkins et al. 2008; Naikar et al. 2005; Rechard et al. 2015). Particularly, those familiar with the principles and techniques of traditional systems engineering would be more likely to have misconceptions about AH (Naikar 2013; Ostaeyen et al. 2013). One critical misconception is that they regard 'structural goal-means relationships' in the AH model as the same as 'part-whole' relationships of the part-whole decomposition model. As explained in section 2.2, although these two models are coupled, they are conceptually different. The other crucial misconception is that 'structural goal-means relationships' are considered as the same as 'action goal-means relationships'. Let's suppose again that a current goal is the moving of two persons from A to B. Two structural means can be an automobile and a bus, all of which are expressed as noun to specify that they are not actions but objects. However, action means can be expressed as follows: leading two persons to a bus stop, waiting for the next bus coming to the stop, and letting them ride on the next bus, etc.

Even if they understand the concepts and principles of AH, they have another difficulty applying it to the modelling of work domain knowledge in a systematic way. As in the use of other modelling methods, a lot of experiences in the use of AH would be the most effective way for lessening the difficulties. Additionally, there is not yet a formal process of using AH; therefore, the quality of the work domain knowledge model based on the AH still depends much on the expertise and experiences of knowledge modellers. However, the principles and guidance for using AH, which are based on a sound theory of work domain system, can be an effective means for supporting its systematic use (Naikar 2013).

Among the five abstraction levels of AH, two higher functional levels, which are GF and AF, are significant for improving the performance of knowledge intensive works (Ham and Yoon, 2001; Ham et al. 2008; Vicente 2002). Studies on user interface for complex systems also acknowledge the benefits of knowledge on the two levels in a range of work situations (Burns and Hajdukiewicz 2004). Then an arising research question is how to model two higher functional levels more consistently and systematically. It seems that LST can be effectively used for this purpose because the categorized subsystems of LST can be a useful reference for basic functional units of GF and their relationships in terms of mass-energy or information can be meaningfully considered for modelling AF.

Another important information identified by the use of AH, which has been found to be critical to enhance the performance of knowledge-based works, is the goal-means relationships between the different levels in AH (Ham and Yoon 2001; Jenkins et al. 2008; Naikar 2013). However, it is never easy, particularly for a novice user of the AH, to identify meaningful goal-means relationships in the AH for a work domain as well. Concepts and principles underlying LST can be effectively used as a reference for identifying goal-means relationships of a work domain.

From the descriptions above, it can be said that the combined use of AH and LST for modelling work domain knowledge would be a better approach. With this issue in mind, this study proposes a new approach of modelling work domain knowledge based on a combined use of AH and LST. A conceptual framework for integrating AH and LST and a process for using the proposed method are proposed. Considering that the nature of both

AH and LST can be widely used for all kinds of work domains, a new approach would be generalizable to a lot of work domains.

3. Proposed method for modelling work domain knowledge

3.1 Combined use of AH and LST

Figure 3 illustrates a framework for combining AH and LST. Of the five levels in the AH, it is rather easy to identify and model information at three levels (FP, PF, and P). Once the scope and boundary of a work domain are determined, FPs can be identified from several sources, such as design manuals. As P-level information is about visible physical objects and their layout and spatial relationships, it can be identified without any great difficulty. As PF-level information is concerned with the physical states of components and physical objects identified at P-level, it can be obtained by examining their exhibited behaviour.

<Figure 3. Framework for combining the AH and LST>

However, it would not be easy to identify information at the remaining two function levels (AF and GF), which are critical to enhance the cognitive performance of knowledge workers in a system. The 20 subsystems specified in LST can be a useful referential point for identifying GF-level information. Considering functional purposes and examining available resources concerned with the design of a work domain, one can think of all of the functions implemented for achieving FPs in terms of mass/energy/information/money. And then those functions can be meaningfully categorized and organized by referring to the 20 subsystems of LST.

The relationships between subsystems, which are judged to be associated with a work domain, and generalization of the subsystems can give useful hints for discovering causal structure and flows of mass/energy/information/money that should be identified at AF-level. And some priority measures and quality indicators, such as usability and performance, should be identified as well at this level. These measures and indicators can be effectively used to coordinate and balance GF-level functions when they sometimes conflict.

3.2 Process of using the proposed method

Modelling work domain knowledge based on AH can be done in various ways; there is no general process on how to use AH for work domain knowledge modelling. This study proposes a process of modelling work domain knowledge, which specifies how to identify information at each five levels of AH in what order by referring to LST (Figure 4). Three types of knowledge should be identified as the results of work domain knowledge modelling: functional information at each level of AH, goal-means relationships between functions at adjacent abstraction levels, and topological links between functions within an abstraction level.

<Figure 4. Process for using the proposed method>

Firstly, the scope and boundary of a work domain to be modelled should be clearly determined. One of the frequent mistakes that analysts make is to model functions existing outside a work domain. Thus knowledge modellers should attempt to avoid making such a mistake. Of the five abstraction levels, FPs should be firstly identified. Then GF-level functions, P-level information, and PF-level functions should be identified in sequence. GF-level functions need to be modelled again by referring to functions identified at the level of PF. The initial set of GF-level functions are identified by referring only to FPs and 20 subsystems of LST, without considering PF-level functions that are actually implemented to realize GF-level functions. It is therefore important to refine the initial set of GF-level functions after identifying PF-level functions, abstracting PF-level functions and matching the abstracted functions with the functions of the initial set. AF-level functions should be identified lastly based on the finalized set of functions of GF-level. Two main functions of AF-level information is to indicate how GF-level functions work together in order to achieve FPs and to offer some measures to be used for judging whether FPs are well achieved or not. Accordingly, when identifying AF-level functions, measures for setting the priority of each GF-level function should sometimes be identified in relation to quality criteria such as effectiveness and efficiency. After modelling each abstraction levels of AH, knowledge modellers should discern all of the goal-means relationships between functions at adjacent abstraction levels. It is also important to identify the interrelationships between functions within a same abstraction level, which is called topological links.

As explained previously, the concept of AH is conceptually differentiated from the concept of part-whole physical decomposition that is commonly used in a traditional system modelling. However, if information about part-whole decomposition (system-subsystem-component) of a work domain is identified together, work domain knowledge can be more comprehensively modelled. For this reason, it is recommended to identify 'part-whole' structure of a work domain as well.

The proposed process can be useful for enhancing the quality of work domain models as well as improving the process of work domain modelling. As is usual with other knowledge modelling methods, there may be a difference in knowledge modellers' ability and attitude of identifying meaningful work domain knowledge based on the AH. Such a difference sometimes could lower the validity of work domain models. Therefore it can be said that the proposed process could be effective in minimizing the difference of knowledge modellers. Considering that there is not yet a formalized process of using AH for work domain modelling, the proposed process could be a basis for or give some useful cues for establishing a formalized process.

4. Application example

4.1 Work domain description

The work domain that is used for an application example of the proposed method is the simplified secondary cooling system of nuclear power plants (NPPs) (Figure 5). Primary cooling system of NPPs generates thermal energy by the operation of nuclear reactor, and secondary cooling system produces electricity by the operation of turbine using thermal energy transferred from the primary cooling system. Secondary cooling system also circulates feedwater continuously to keep the pressure of primary cooling system within a safe boundary. Thus, the purposes of the secondary cooling system are to maximize productivity of electricity generation and manage water flow closely related to the safety of NPPs. The important characteristic of the secondary cooling system is that water exists in a two-phase mixture of steam and liquid. This increases the complexity of controlling the system.

<Figure 5. Work domain for application example (simplified secondary system of NPPs)>

Secondary cooling system is composed of four subsystems: steam generation system (SGS), turbine operation system (TOS), condensation system (COS), and feedwater supply system (FSS). SGS boils feedwater provided from FSS and generates steam to be transferred to TOS. The components of SGS include steam generator (SG1, SG2), steam dump valve (SDV1, SDV2), and steam isolation valve (SIV1, SIV2). TOS runs turbines to produce electrical energy by using steam from SGS, so that thermal energy is transformed to electrical energy in this system. The components of TOS are turbine control valve (TCV), high pressure turbine (HPT), low pressure turbine (LPT1, LPT2), low pressure turbine isolation valve (LPTIV), and generator (GEN). COS condenses steam into water (feedwater) to be used in steam generator. The components of COS are condenser (CON1, CON2), condenser isolation valve (CIV1, CIV2), condensation pump (CP1, CP2). FSS is concerned with transferring feedwater to SGS. The components of FSS are low pressure heater (LPH1, LPH2), high pressure heater (HPH1, HPH2), feedwater pump (FP1, FP2), feedwater control valve (FCV1, FCV2), and feedwater isolation valve (FIV1, FIV2).

Three types of valves are used in order to control the flow of water (steam). The first is isolation valve, which is usually opened under normal situations. However, the isolation valve should be closed to block the flow of water (or steam) when the state of monitoring variables related to the water (steam) flow shows extremely high value. The second is dump valve that is usually closed under normal situations. Human operators should open a dump valve in order to release steam in steam generator when pressure of steam generator approaches high hazard region. The last is control valve, on which human operators can manipulate the flow of water (steam) quantitatively, whereas, isolation and dump valve have only two states (open and close). The state of a control valve is dependent on human operators' control action.

4.2 Modelling work domain knowledge

The knowledge of the secondary cooling system can be analysed and modelled by the use of the proposed method. Functional purposes of the work domain are to maximize productivity of electricity generation and keep the system safe by managing water and steam flow properly. To identify initial set of GF-level functions, 20 subsystems of LST are considered with the following questions: whether or not each of 20 subsystems is related to the secondary cooling system to realize the functional purposes, and how they are implemented in the system if they are related to it. Through this knowledge analysis, we can identify four main GF-level functions: heat transfer including heating and cooling, mass flow, feedback control, and power supply. Additionally, we can obtain some useful information for identifying functions at other abstraction levels through the analysis based on LST. Table 5 shows mapping between the functions of the work domain and subsystems of LST and their abstraction levels.

<Table 5. Mapping between the functions of the work domain and subsystems of LST and abstraction levels of AH>

Here three examples will be described. The function of reproducer subsystem is to generate other subsystems similar to itself. In the work domain, there are two similar subsystems being concerned with two different states of same mass material, each of which is respectively water (liquid state) and steam (gas state). The circulation that water is transformed into steam and steam is again transformed into water happens in the work domain. Such a reproducing function is essential to achieve the functional purpose of the work domain: generating electricity and keeping safety. Thus mass flow function can be regarded as a GF-level function in terms of reproducer subsystem. However, the amount of water should always be the same as that of steam; law of conservation of mass should be satisfied in order to keep the work domain safe. From this, we can think that reproducer subsystem gives a cue for identifying AF-level function as well: conservation of mass in consideration of the meaning of AF-level information. Extruder subsystem can be considered as the second example. The function of extruder subsystem is to transmit matter-energy in the form of products and waste out of the system. It can be easily considered that this subsystem is related to generating electricity in the work domain. Thus power supply function can be identified at the GF-level, in association with extruder subsystem.

Additionally, the amount of electrical energy generated at the TOS should be the same as the amount of steam energy coming from the SGS. This indicates that extruder subsystem gives a hint for identifying AF-level function: conservation of energy. As the third example, we can consider storage subsystem of which the function is to retain deposits of matter-energy in the system for specified periods of time. Two subsystems in the work domain are concerned with storage of mass and energy: SGS and COS. One critical function to be satisfied in these storages is to keep the amount of input mass and energy as the same as that of output mass and energy. Thus storage subsystem of LST is associated with the two AF-level functions: conservation of mass and conservation of energy.

P-level information includes the appearance, condition, and location of each component (e.g., steam generator, heater, and valve), and spatial proximity among the components. Each component exhibits its dynamic behaviour; the state of each component or four subsystems of the work domain can be represented by monitoring variables. Table 6 shows the list of monitoring variables and their labels. The work domain has 11 monitoring variables that human operators should continuously observe in order to assess the dynamic states of each component, subsystems, and the work domain. Each monitoring variable should be controlled within a range between its maximum and minimum levels to meet the safety demands. When a fault occurs at a component, some of the monitoring variables can rapidly approach the maximum or minimum level, and the system can run into emergent situation. In such a case, to control the variables effectively, human operators properly need to understand the work domain knowledge. The work domain also has control variables that can be manipulated by human operators to change the system's state. Considering the dynamic states of each component and monitoring and control variables, we can identify PF-level functions, which include steam generation, condensation, feedwater heating, feedwater/steam stream, flow control, and turbine operation.

<Table 6. List of process variables and their labels>

Based on the PF-level functions identified above, we can re-examine the initial set of GF-level functions and refine them by abstracting the PF-level functions and referring to the mappings shown in Table 5. The initially identified functions at the GF-level are: heat transfer, mass flow, feedback control, and power supply. And the identified PF-level functions are: steam generation, condensation, feedwater heating, feedwater/steam stream, flow control, and turbine operation. All of the PF-level functions should have goal-means relations with any GF-level functions. We can examine these relations as follows: (1) the abstracted purpose of steam generation is to heat water and transform it into steam; thus it is connected to heat transfer (heating), (2) the abstracted purpose of condensation is to cool steam and transform it into water: thus it is connected to heat transfer (cooling), (3) the abstracted purpose of feedwater heating is also concerned with heat transfer (heating), (4) the abstracted purpose of feedwater/steam stream is to move mass; thus it is related to mass flow, (5) the abstracted function of flow control is to regulate the flow of mass, which is concerned with feedback control, (6) the abstracted purpose of turbine operation is to supply electricity power; thus it is linked to power supply. There is no GF-level function which does not have a relationship with any PF-level functions. It is accordingly judged through this further analysis that four functions identified in the initial set were sufficient to model the GF-level of the work domain. AF-level information in process control systems like the work domain is usually represented by the causal relations of mass and energy. In this case study, the causal relations are represented in terms of the conservation of mass and energy for steam generator and condenser. The functional purposes of the work domain justify the reason for why the conservation laws of mass and energy should be kept. The AF-level functions work as the basis for accomplishing the functional purposes. Figure 6 shows functional information at each level of AH in the work domain, which is identified by the proposed method.

<Figure 6. AH representation of simplified secondary system of NPPs>

After identifying the information within each level of AH, it is necessary to identify and represent the relationships among the functions across the levels. For this, we can use the knowledge analysis results shown in Table 5; subsystems of LST that are related to more than one abstraction level can be a referential point for identifying meaningful goal-means relationships. Figure 7 illustrates how the functions at different abstraction levels are related in terms of goal-means relationships. An important structural feature shown in Figure 7 is the many-to-many relations among functions of adjacent levels. That is, a goal in the upper level can be achieved by several means in the lower level and, conversely, a means can be used for several goals. For example, Mass Flow 2 in GF has relationships to both the Mass 1 source and Energy 1 source. Referring to Figure 5, Mass 1 Inventory is composed of the two steam generators (SGs). Then, their levels and pressures determine Mass 1 balance and Energy 1 balance, respectively. When human operators change the input flow rate to the two SGs (i.e. Mass 1 Inventory), they should consider how this change would influence the pressure and the level of the two SGs (i.e. Energy 1 balance and Mass 1 balance). Figure 8 illustrates how the functions are related each other within each abstraction level (topological links).

<Figure 7. Mapping between levels of AH of the work domain>

<Figure 8. Relationships within levels of AH of the work domain>

5. Concluding Remarks

This study proposed a new approach to analysing and modelling work domain knowledge with the combined use of AH and LST. AH has been widely used for modelling the knowledge of a work domain, particularly a complex socio-technical system such as power plants and healthcare systems; however, practitioners have still difficulty using it systematically. Of the five abstraction levels of AH, it is comparatively more difficult to identify the functions at AF- and GF-levels and goal-means relationships between functions at adjacent levels. In order to help identify and model them, this study suggests the use of the concepts and 20 subsystems specified in LST. The proposed method offers a framework for combining AH and LST and a process for modelling work domain knowledge. An application example of modelling the knowledge of a simplified secondary system of NPPs was described as a case study. This case study showed that the proposed method could be a useful method for work domain knowledge modellers by lessening difficulties pointed out in the use of AH.

This study has limitations to be noted and further studied. Firstly, the proposed method would be more useful for technology-oriented engineering systems such as power plants than human activity-oriented systems such as banking systems. Technology-oriented engineering systems are designed on the basis of physical laws and general engineering principles, most of which could be explained in terms of mass/energy/information processing. Thus technology-oriented engineering systems are highly structured and their subsystems and functions are tightly coupled. For this reason, the combined use of AH and LST could be more useful in these domains. However, human activity-oriented systems are generally governed by human purposeful activities; thus it is likely that the functions of these systems cannot be modelled in terms of mass and energy processing. Particularly, it could not be meaningful to model AF-level functions of these types of systems in terms of mass and energy causal structure. This would be a barrier to apply the proposed method to human activity-oriented systems. It is therefore necessary to reflect those points to the proposed method in order to secure more generalizability. Secondly, more case studies in a wide range of work domains should be developed. Through more case studies, the conceptual and methodological bases of the proposed method can be more enriched, and its usefulness will be more justified.

Acknowledgements

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Table 1. Meaning of five abstraction levels in the AH

Abstraction Level	Represented Functions and Characteristics	
Functional Purpose (FP)	The ultimate functions that a system should accomplish; The constraints that should be considered in the interaction between a system and its environments	↑ The Causes of Abnormal working states / ↓ The reasons for normal working states
Abstract Function (AF)	Causal structure in terms of mass, energy, information, value, etc.; A set of criteria that determines the priority of GF-level functions and the way that GF-level functions work together	
Generalized Function (GF)	Purpose-related functions to achieve the ultimate functions of FP	
Physical Function (PF)	Functions to achieve to implement GF-level functions, which are identified from the behaviours and states of physical components and devices	
Physical Form (P)	Actually visible forms (e.g. shape and colour) and layout of components and devices designed in a system	

Table 2. Examples of AH-based work domain knowledge modelling (Rasmussen (1986))

Abstraction Level	Washing Machine	Computer System	Manufacturing Plant
Functional Purpose (FP)	Washing specifications Energy waste requirements	Decision flow graphs in problem terms	Market relations Supply sources Energy and waste constraints Safety requirements
Abstract Function (AF)	Energy, water, and detergent flow topology	Information flow Operations in Boolean logic terms, truth tables Symbolic algebraic functions and operations	Flow of energy and mass, products, monetary values Mass, energy balances Information flow structure in system and organization
Generalized Function (GF)	Washing, draining, drying Heating, temperature control	Memories and registers, Amplification, analogue integration and summation Feedback loops, power supply	Production, assembly, maintenance Heat removal, combustion, power supply Feedback loops
Physical Function (PF)	Mechanical drum drive Pump and valve function Electrical/gas heating circuit	Electrical function of circuitry, Mechanical function of input-output equipment	Physical functioning of equipment and machinery Equipment specifications and characteristics Office and workshop activities
Physical Form (P)	Configuration and weight, size Style and colour	Physical anatomy Form and location of components	Form, weight, colour of parts and components Their location and anatomical relation Building layout and appearance

Table 3. Work domains or application problems using the AH

Work Domains or Application Problems	Examples of Studies
Process control systems	(Ham and Yoon 2001; Ham et al. 2008; Lind 2003; Yim et al. 2011)
Air traffic control systems	(Ahlstrom 2005; Ho and Burns 2003)
Healthcare systems	(Effken et al. 2011; Hajdukiewicz et al. 2001; Miller 2004; Wu et al. 2012)
Military systems	(Burns et al. 2005; Lintern 2006; Bennett 2014)
Network management	(Burns et al. 2003)
Vehicle systems	(Jansson et al. 2006; Mendoza et al. 2011; Regan et al. 2015)
Car Driving and Road Design	(Cornelissen et al. 2015; Rechard et al. 2015; Stevens and Salmon 2014)
Financial systems	(Achonu and Jamieson 2003)
Training systems	(Naikar and Sanderson 1999)
Software systems	(Kwon et al. 2007; Leveson 1999)
Information retrieval and digital library	(Xie 2006; Xu et al. 1999)
Manufacturing system	(Higgins 1999; Upton and Doherty 2008)
Design process and Product design	(Burns and Vicente 1995; Fu et al. 2006)
Automation design	(Mazaeva and Bisantz 2007)
Evaluation of design proposals	(Naikar and Sanderson 2001)
Team design	(Naikar et al. 2003)
Organization of usability factors	(Ham et al. 2006)
Classification of usability problems	(Ham 2014)
Inputting visualization data	(Wright et al. 2013)
Consumer electronics design	(Mazaeva and Bisantz 2013)
Product-Service system design	(Ostaeyen et al. 2013)
Technology management in Systems	(Jenkins et al. 2011)
Data Quality Verification	(Page et al. 2014)

Table 4. Categorized subsystems of LST

Subsystems		Functions of Subsystems
Processing matter/ energy/ information	Reproducer	Generates other subsystems similar to itself
	Boundary	Separates the system from its environment
Processing Matter/ energy	Ingestor	Transports matter-energy across the boundary from the environment
	Distributor	Carries matter-energy around within a system or subsystem
	Converter	Transforms matter-energy inputs into forms more useful to the system or subsystem
	Producer	Forms stable associations among matter-energy inputs to the system or outputs from its converter
	Storage	Retains deposits of matter-energy in the system for specified periods of time
	Extruder	Transmits matter-energy in the form of products and waste out of the system
	Motor	Moves the system or parts of it in relation to part or its entire environment
	Supporter	Maintains the proper spatial relationships among components
Processing Information	Input transducer	Brings markers bearing information into the system
	Internal transducer	Receives markers bearing information that has been generated or processed within the system into a subsystem of the system
	Channel and net	Routes markers bearing information to all parts of the system
	Timer	Transmits to the decider information about time-related states of the environment or of components of the system
	Decoder	Alters the code of input information into a private code used by the system
	Associator	Forms enduring associations among units of information in the system (1st stage of learning)
	Memory	Stores various types of information in the system for different periods of time (2nd stage of learning)
	Decider	Receives information inputs from all other subsystems, processes them, and decides something
	Encoder	Alter the code of information into the public code that can be used by other systems in environment
	Output transducer	Transports markers bearing information out of the system across the boundary

Table 5. Mapping between the functions of the work domain and subsystems of LST and abstraction levels of AH

Subsystems	Functions of the work domain	Abstraction levels
Reproducer	Circulation system of water and steam	AF, GF, PF
Boundary	Walls of the building containing secondary system	P
Ingestor	Receiving reactor input (mass source, energy source)	AF
Distributor	Mass flow, Heat transfer (heating, ,cooling), Feedwater and Steam stream, Feedwater heating, Condensation	AF, GF
Converter	Condensation, Steam generation,	PF
Producer	Causal structure of mass/energy input and output	AF
Storage	Mass inventory, Energy inventory	AF
Extruder	Generating electricity (mass sink, energy sink), Power supply	AF, GF
Motor	N/A	
Supporter	The building containing secondary system	P
Input transducer	Receiving reactor output, Feedback from generator to TCV	PF
Internal transducer	Sensing level, pressure, and temperature of steam generator	PF
Channel and net	Communication line	P
Timer	Feedback control, Flow control	GF, PF
Decoder	Feedback control, Flow control	GF, PF
Associator	N/A	
Memory	N/A	
Decider	Feedback control, Flow control	GF, PF
Encoder	Calculating the electric power	PF
Output transducer	Sending the electric power to main control centre	PF

Table 6. List of process variables and their labels.

Monitoring variables related to system state
(Level variables; L_ means level of)
L_SG1, L_SG2, L_CON1, L_CON2
(Pressure variables; P_ means pressure of)
P_SG1, P_SG2, P_HPT, P_FW1, P_FW2
(Temperature variables; T_ means temperature of)
T_FW1, T_FW2
(Flow rate variables; F_ means flow rate of)
F_SDV1, F_SDV2, F_SIV1, F_SIV2, F_FIV1, F_FIV2
F_FCV1, F_FCV2, F_TCV, F_LPTIV, F_CIV1, F_CIV2
F_CP1, F_CP2, F_FP1, F_FP2
(Heat rate variables; H_ means heat rate of)
H_HPH1, H_HPH2, H_LPH1, H_LPH2
(Others)
T_RO: temperature of reactor output
F_RO_SG1: flow rate from reactor output to SG1
F_RO_SG2: flow rate from reactor output to SG2
D_EP: demand of electricity
Control variables
(Variables with binary states)
SDV1, SDV2, SIV1, SIV2, FIV1, FIV2, LPTIV, CIV1, CIV2
CP1, CP2, HPH1, HPH2, LPH1, LPH2
(Variables with quantitative states)
FCV1, FCV2, TCV, FP1, FP2

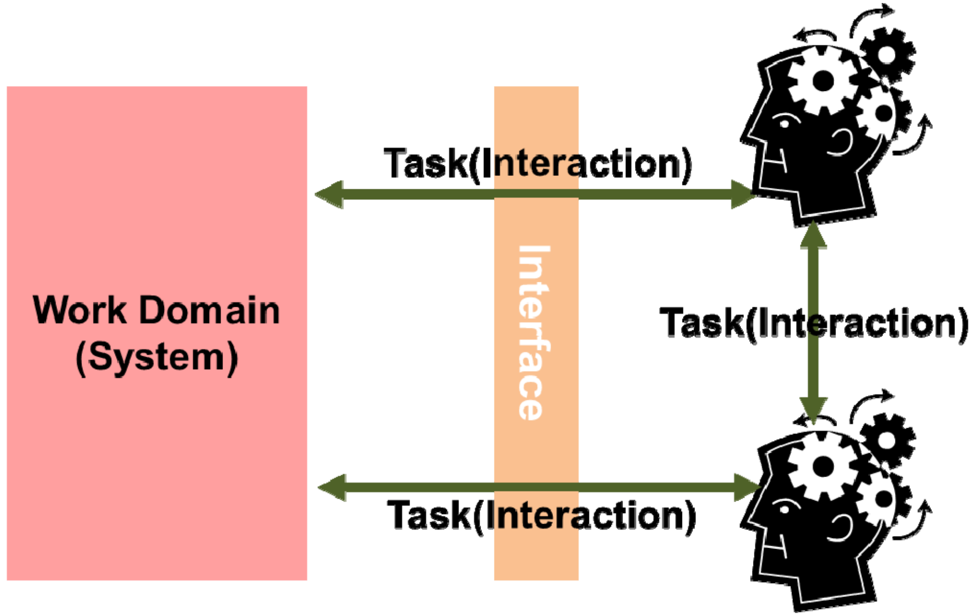

Figure 1. General model of HSI and the concept of work domain

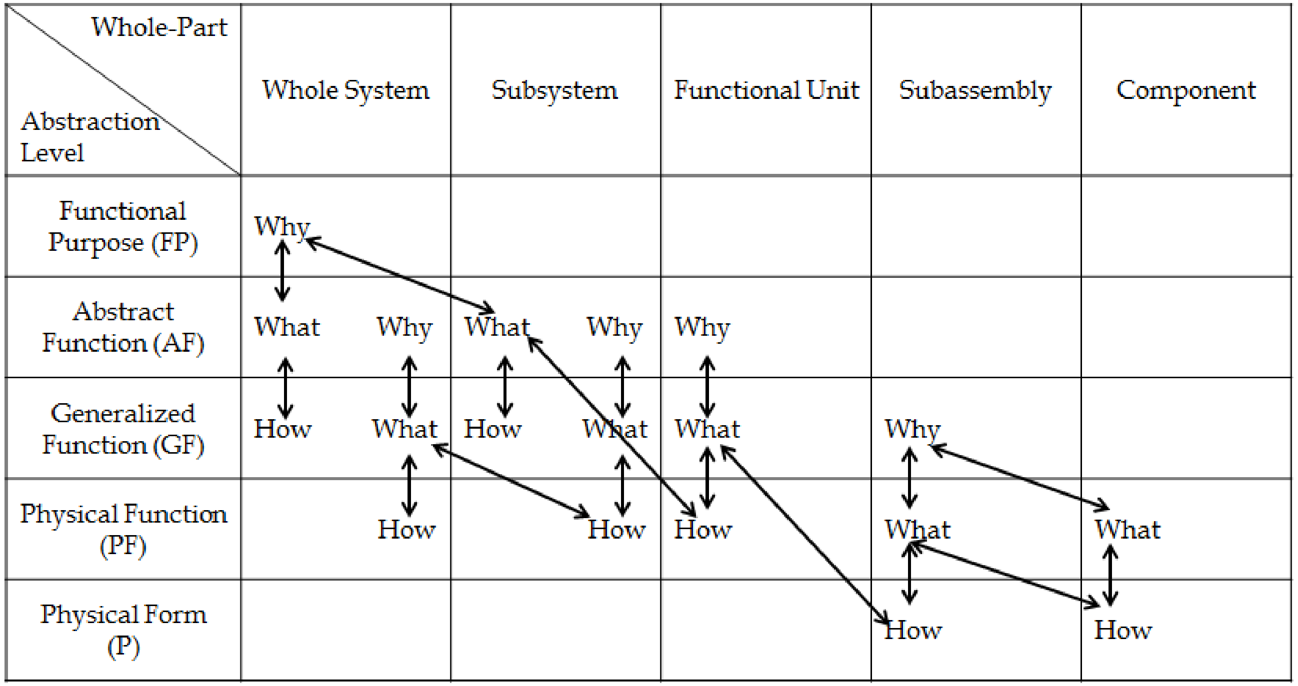

Figure 2. Abstraction-Decomposition space for a work domain

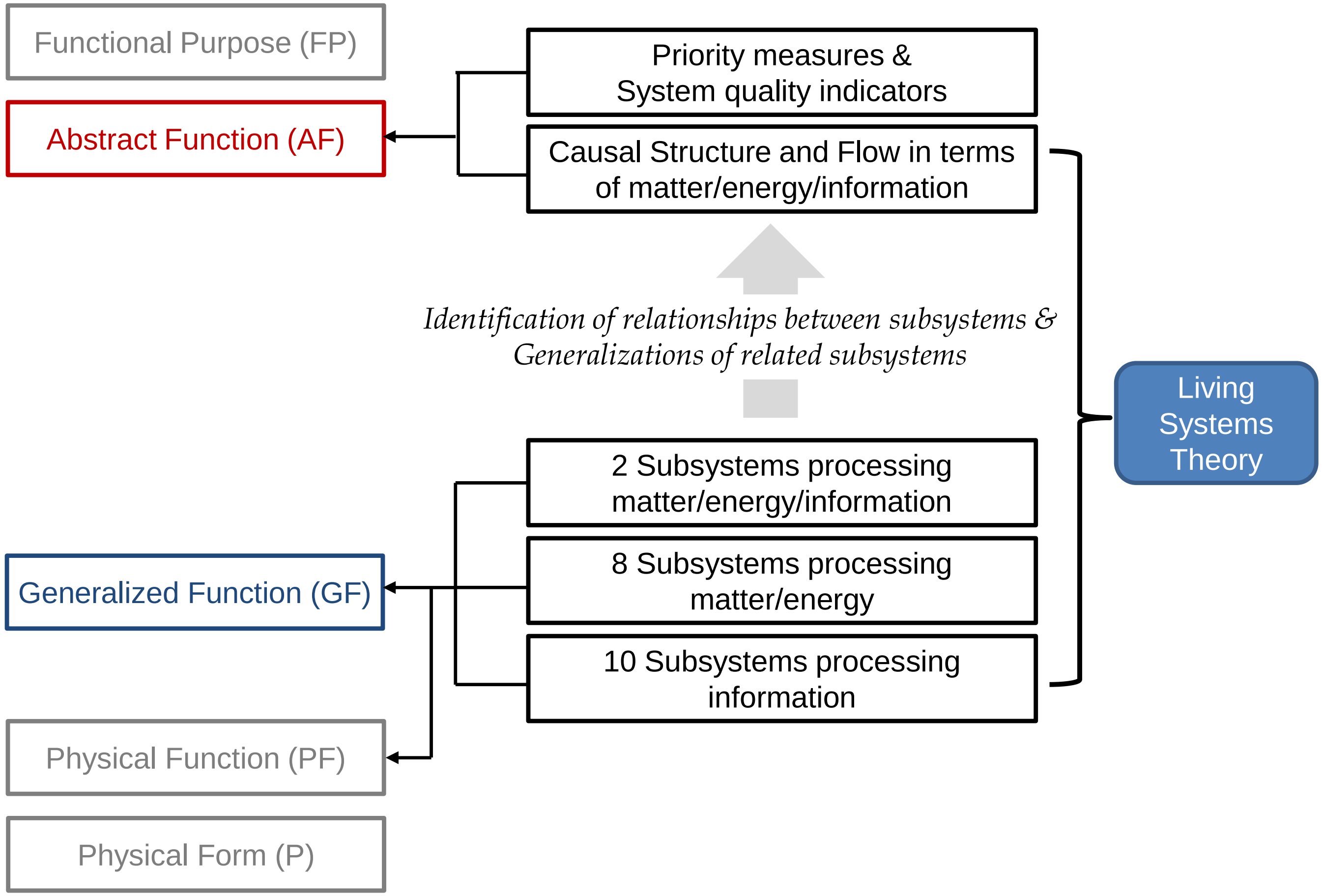

Figure 3. Framework for combining the AH and LST

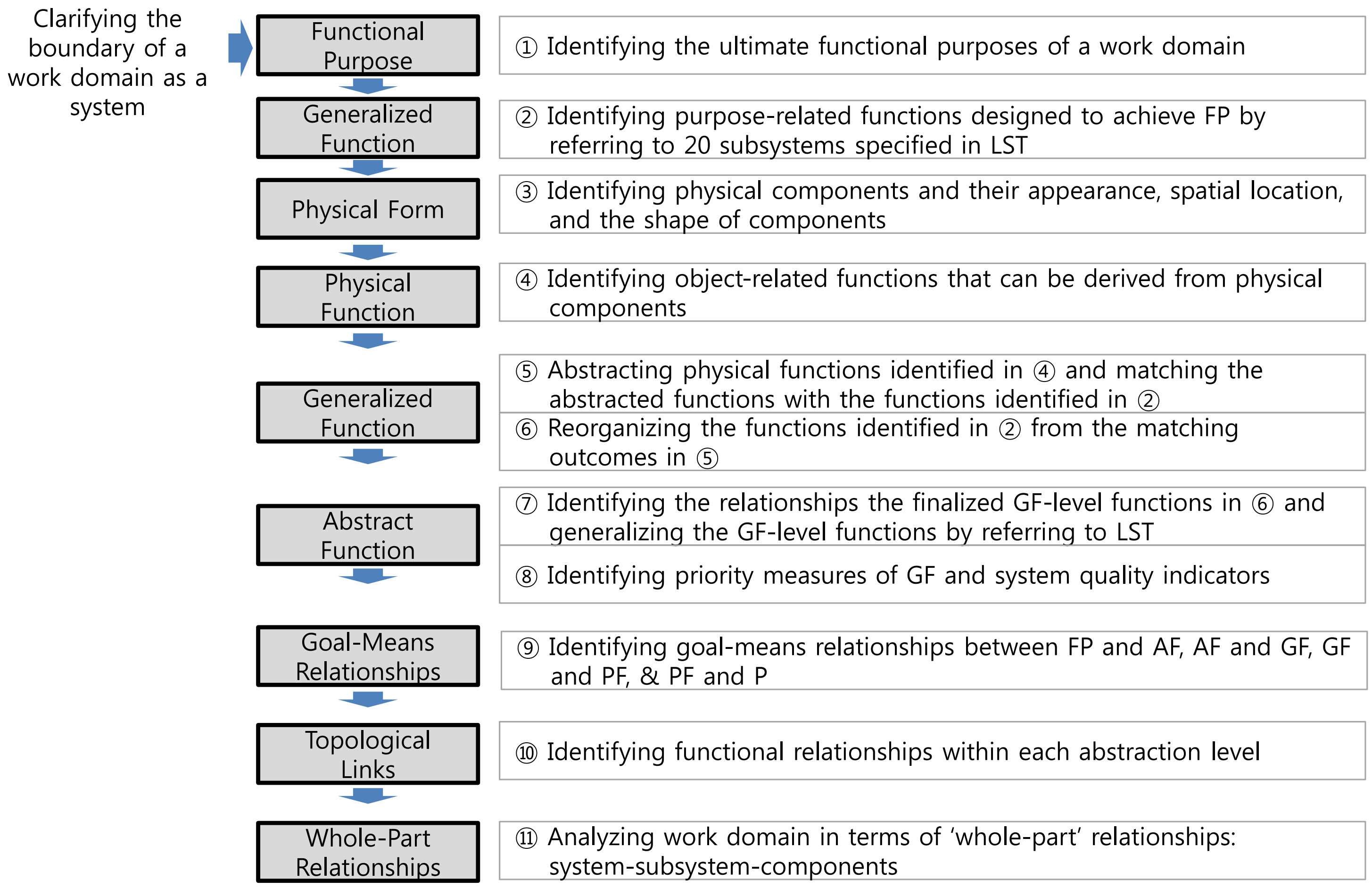

Figure 4. Process for using the proposed method

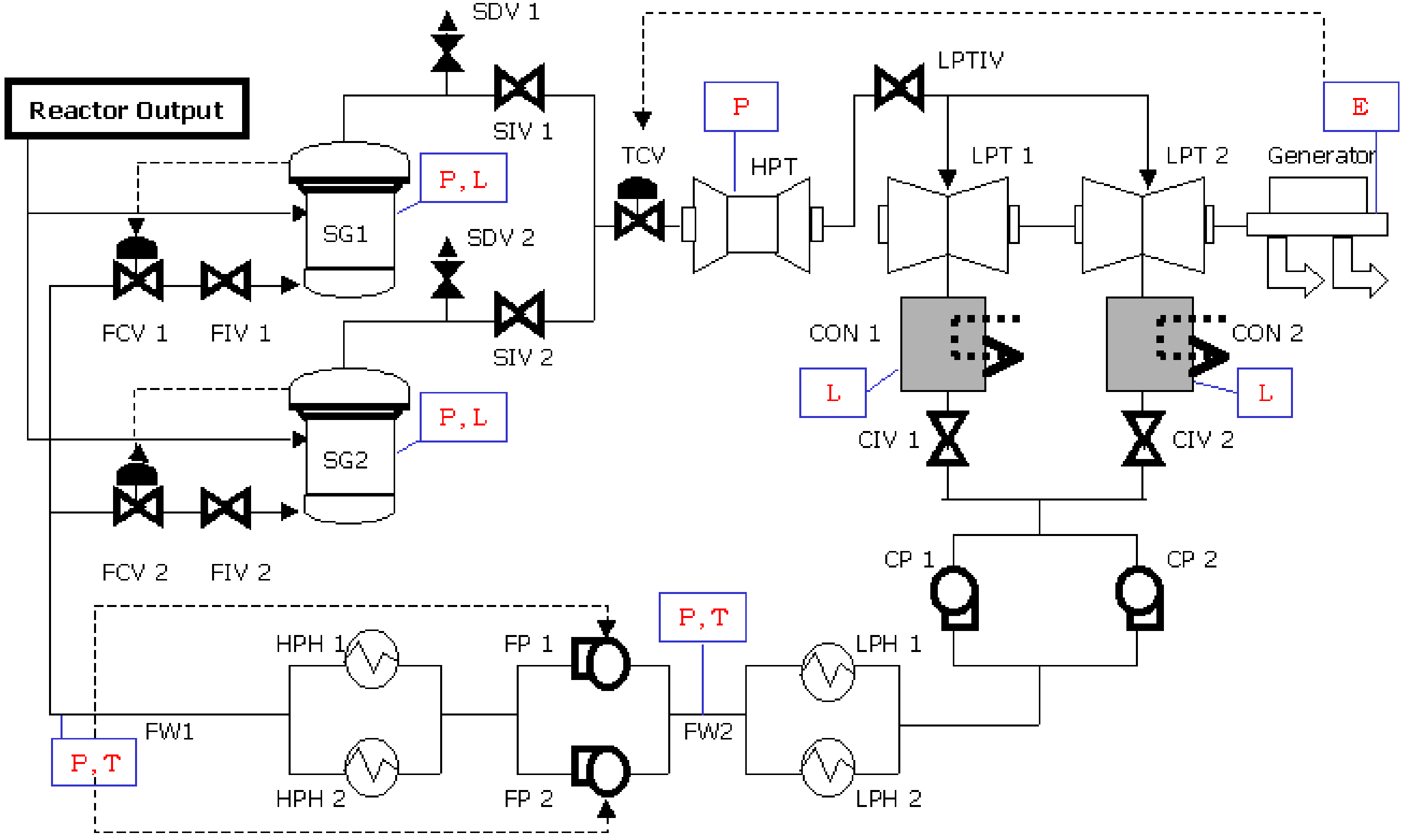

Figure 5. Work domain for application example (simplified secondary system of NPPs)

Level	Properties
Functional Purpose (FP)	Generate electricity as demanded Keep safety
Abstract Function (AF)	Conservation of mass (feedwater & steam) (Mass 1 inventory related to steam generators (SG1 & SG2), Mass 2 inventory related to condensers (CON1 & CON2)) Conservation of energy
Generalized Function (GF)	Heat transfer (heating, cooling) Mass flow (Mass flow 1 related to the flow from COS to FSS, Mass flow 2 related to the flow from FSS to SGS) Feedback control Power supply
Physical Function (PF)	Steam generation Condensation Feedwater heating Feedwater/steam stream Flow control Turbine operation
Physical Form (P)	Spatial layout Appearance

Figure 6. AH representation of simplified secondary system of NPPs

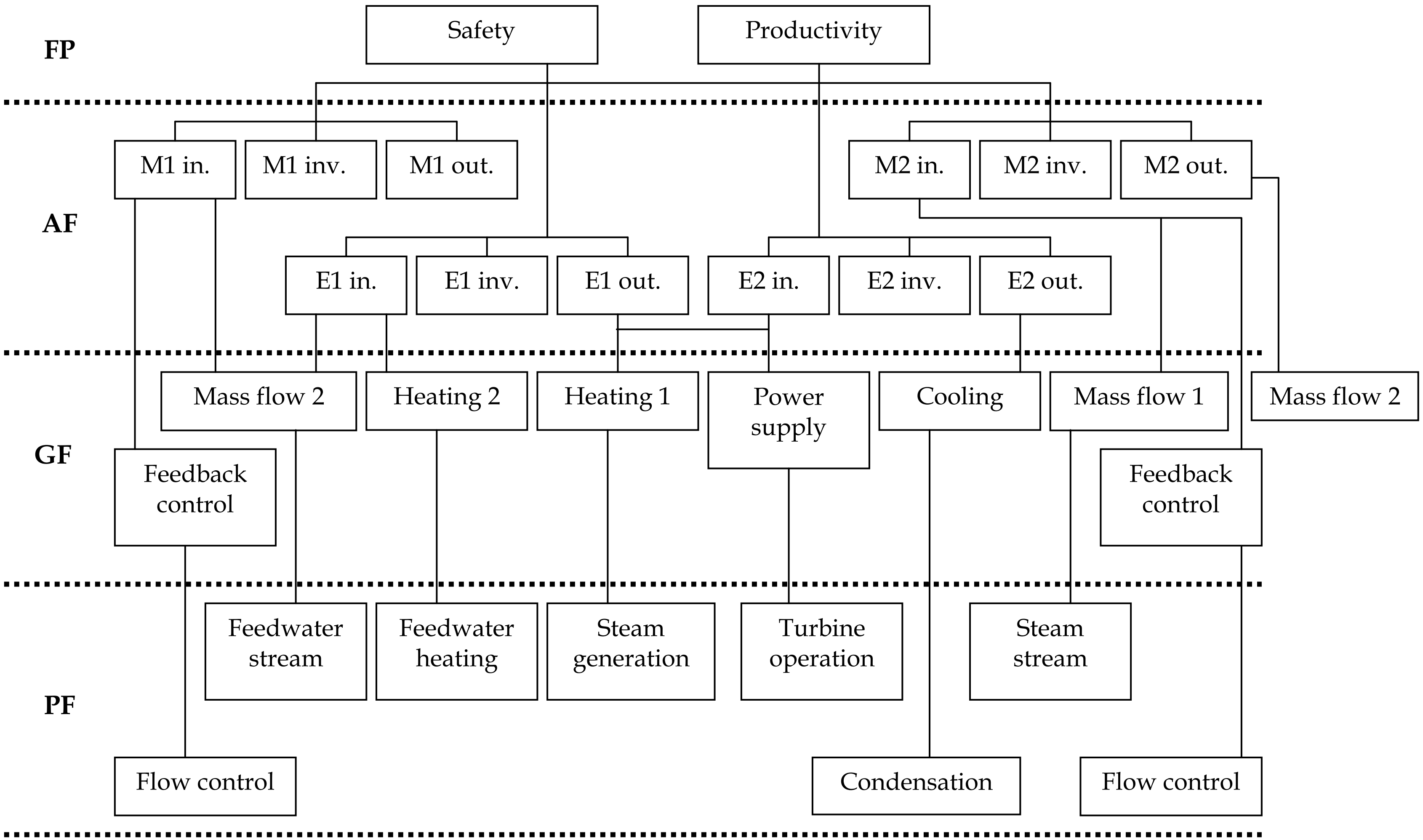

Figure 7. Mapping between levels of AH of the work domain

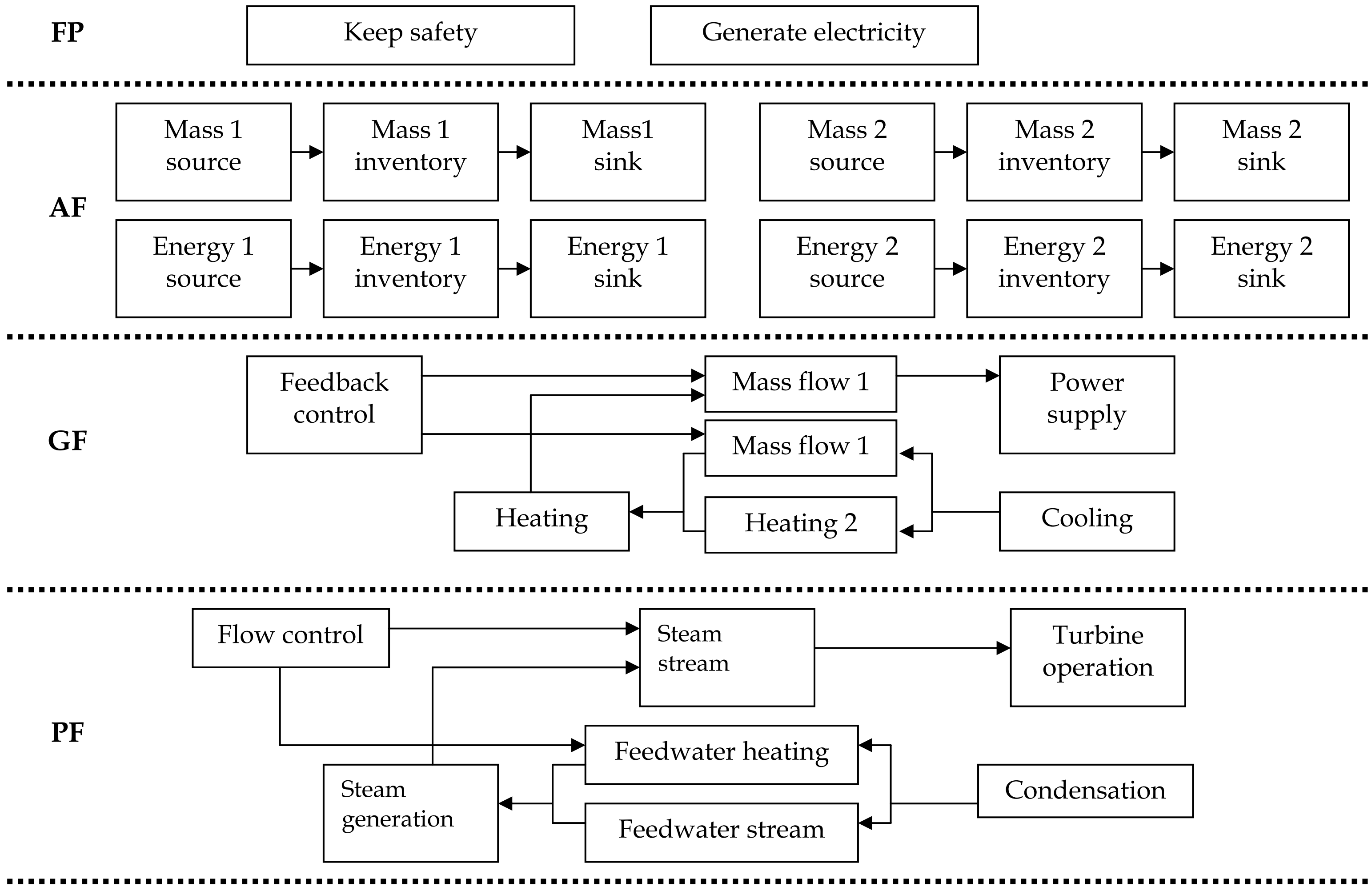

Figure 8. Relationships within levels of AH of the work domain