A Risk Model for Indoor Environment Safety

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***Abstract*—Indoor environment could be hazardous to occupants, so hazard information for detection, prediction and reaction becomes necessary. In order to provide comprehensive hazard information, this research proposed the concept of *Performers System* with the purpose of applying STAMP (Systems-Theoretic Accident Model and Process) model to indoor environment safety. The STAMP model is based on general system theory, which expands the traditional model of accident causation. Then a risk model that supplement STAMP is proposed, which together characterize and analyze hazardous indoor environment situations. The risk model introduces hazard formation mechanism related to indoor environment that can provide rich information for hazard detection, and the hazard formation pattern information for hazard prediction. The original STAMP is a powerful tool for modeling accident causation and can be used to identify hazards and to analyze their causes. Then hazard reaction takes advantage of the causes. The risk model also gives the right timing for precaution reaction and remedial reaction. And typical examples will be given to shown the appropriateness of the risk model.**

***Keyworkds*—Accident Model, Indoor Environment Safety, STAMP**

I. Introduction

People spend the majority of their time indoor[5]. Abnormal variation of indoor environment may cause hazardous situations and result in undesired consequences[9] of directly or indirectly harming occupants. For example, high or low thermal condition affects sleep that may result in health problems and reduce life quality[1]; high temperature and humidity can cause heat related diseases or even death especially to old people and young children[2][3]. Abnormal thermal conditions may also result in slow to react or inappropriate judgement[4] that may cause accident in nursing old people or taking care of young children. So, an accident model that characterizes and analyzes hazardous situations that can be used in risk assessment in order to provide comprehensive information regarding hazard detection, prediction and reaction becomes critical.

The STAMP model[8] is a newly developing technique, which is based on general system theory and expanded the traditional models of accident causation, e.g. event-based or chain-of-events models[6][7]. However, it cannot be applied to indoor environment safety directly. For one thing, it is not designed for safety problem detection and prediction. Because it doesn't provide mechanism for detectable evidence analysis of hazards. For another, indoor environment is quite different from occupational environment. Indoor environment refers to the indoor space with respect to physical properties that can ensure a comfortable life in some conditions and cause harms in some others, e.g. temperature and humidity may bring thermal comfort and also can result in heat diseases. So indoor environment is not inherently hazardous. Furthermore, In STAMP model, systems are viewed as interrelated components. But traditional home appliances that adjust indoor environment are not interrelated.

In order to apply STAMP model, the concept of *Performers System* is proposed. The performers system takes home appliances and the natural system as performers and consider their behaviors as a whole. The interrelation of home appliances stems from the fact that all devices are interconnected through the same home network and controlled by the same smart home system core. Then based on the performers system, a risk model is proposed that takes advantage of accident causation, which demonstrates hazard formation and provides detectable evidence. The detectable evidence is represented as abnormal variation of physical properties both in time and value domain. The risk model also provides information about the right timing for precaution reaction and remedial reaction based on indoor environment adjustment. Also, typical examples show the appropriateness of the risk model.

The rest of this paper is organized as follows. Second II introduces some preliminary knowledge and discussion about the home and home safety, then a brief introduction of the STAMP model. In section III, the performers system will be given. Section IV introduces the risk model. Finally a conclusion come in section V.

II. Preliminaries

In this section, the concept of home, home safety together with indoor environment safety will be discussed. Then followed by a brief introduction of the STAMP model.

A. Home

A home is the sum of the place where people lives permanently and the social unit – family[14]. Empirically, the place could be a house, apartment etc. to protect the family from unfavourable outdoor conditions like bad weather. And the occupants vary in age, gender and knowledge etc.

1) Partial Automation: As the development of electricity, electronic and networks, the great majority of our life has been automated[9]. Home appliances are equipped with networking capability and various services can be provided through outside network to the home. But, this automated lifestyle is not cover all lifestyles yet. There are still primitive lifestyles left behind as it was. E.g. pots and pans are used in everyday meals. So, a home is a complex environment that part of the lifestyle is automated and the rest is not, as shown in fig.1.

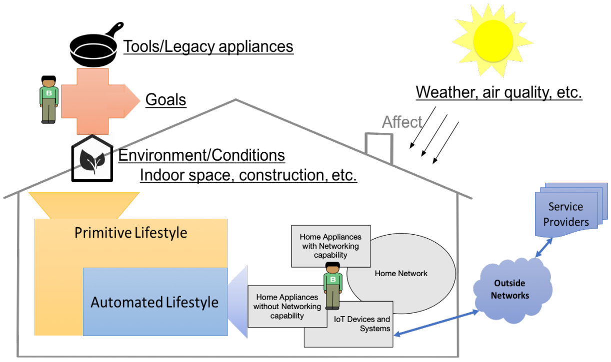

Fig. 1. Lifestyles in a Home

2) Application Area: A home is a place to live. Occupant uses items, e.g. various products, to improve life quality. Occupants are not usually professional, and it is not realistic to make the required items by themselves. Also home items in the market are usually cheap. So items in a home are manufactured from different manufacturers and bought for use in everyday life. For example, high-tech products and furniture. Occupant only need to learn how to use them correctly and safely.

3) The Complex of a Home: As discussed above, a home is complex in its occupants, internal house and external house. Fig.2 shows various items relate to a home. Things from external house are also considered, because they usually affect indoor environment and even lifestyle. For example, hot weather increases indoor temperature; air purifier may be used because of polluted outdoor air quality, etc.

All these items relate to a home involve numerous scenarios that increased the complexity. For example, occupants vary in age, knowledge, etc., the usage scenarios of even the same indoor item are varies. Items may interact with each other, e.g. in cyber world, networking appliances interact with other devices in the network. In physical world, outdoor temperature affects indoor temperature; indoor temperature affects the working status of the air conditioner and also other physical property like humidity. All these make the home complexity.

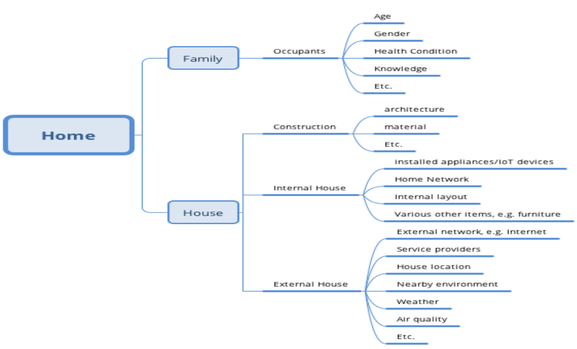

Fig. 2. Various Items Relate to a Home

B. Home Safety

Various safety definitions have been emerged in the literature[11][12][13]. They all concentrate on the desire that consequences of risk will not cause health problems of people, damage to the property or the environment. That is to say risk has been reduced to an acceptable level, e.g. As Low As Reasonably Practicable[11]. Similar to home safety. A home is said to be safe that means an acceptable safety level has been achieved.

Each product or system has its prescribed functionality embedded with specified machine safety, system safety or functional safety, etc. But these safety concerns are restricted by achieving their goals without causing safety problems. There are safety related scenarios may not be covered in product/system design. For example, an air conditioner has the capability to heating/cooling a specified space to achieve the expected effect. If the air conditioner is installed in a bigger room and the material of the house has a good heat conductivity, then expected indoor temperature may not be achieved and could cause safety problems. Or, if a product is used for a different purpose rather than the specification, e.g. because of lack of knowledge, which could also cause safety problems.

Once an item is introduced into the home environment, it also introduced risks. Because an item can not be 100% safe even though the safety techniques discussed in the previous paragraph are embedded in the item design and manufacture. To ensure usage safety, there always attach usage/product safety instruction along with the item. But there are still safety problems occurring with respect to item defect, usage and the usage environment. By expanding the discussion of home safety in [9]. *Home safety* is that risk from internal and external house should be reduced to an acceptable level without harming occupant and damaging to home property. When a hazardous situation is identified, all factors that from physical world and cyber world (depicted in but not limited to fig.2) should be considered. If the causes of the identified hazard can be solved by like engineering. This kind of non-reproducible hazards will not be considered in this paper. But these are still home safety problems.

A home involves a lot of items, so it is necessary to discuss *safety responsibility*. Home safety responsibility attributes safety to the people of two types: the first is professionals. They are the ones who design, manufacture, transport, install and disposal the items. The second is occupants whom usually non-professionals. They are responsible for item usage safety.

Indoor environment safety is an important part of home safety. Indoor environment in this paper refers to the indoor space with respect to physical properties, e.g. indoor temperature, that can ensure a comfortable life in some conditions and cause harm in some others. The situations that could cause harm are usually hazards, e.g. very hot indoor temperature may cause heat stroke for old people and young babies. The proposed risk model in this paper concentrates on the hazard formation of indoor environment and provide evidence for prediction and detection.

C. The STAMP Model

This section gives a brief introduction of the STAMP model, which is referenced from [8]. It is an accident causality model based on general system theory, which systems are viewed as interrelated components kept in a state of dynamic equilibrium by feedback control loops. Based on this model, a comprehensive analysis of identified hazards can be conducted in order to find out their causes.

The STAMP model is built on three basic concepts – safety constraints, a hierarchical safety control structure and process models. Safety constraints are the basic concept in STAMP. Constraints or lack of constraints at a higher level of the hierarchical structure of systems allow or control lower level behavior. A hierarchical safety control structure is because systems are viewed as hierarchical structures, which each level imposes constraints on the activity of the level beneath it. Process model is an important part of control theory. There are four conditions required to control a process, a goal, action condition, observability condition and model condition.

III. Performers System

Indoor environment is adjusted by various home appliances actively, which are controlled by occupants or smart home system core. Or it is adjusted by the natural system passively. Normally, the natural system is the reason of indoor environment formation without intentionally adjustment.

A. The Performers System

Definition 1 (Performer): A *performer* is a network-enabled home appliance that can adjust the indoor environment independently.

There are two types of performers based on the way it adjusts indoor environment. One is direct adjustment, e.g. air-conditioner. It heats or cools indoor air directly; another is indirect adjustment, e.g. electric window. It adjusts indoor temperature by introducing air flow or solar radiation of outdoor environment. In this case, the natural system is part of the performer.

Definition 2 (Performers System): It is a system of all installed *performer*s in a house connected to the home network.

Each *performer* can be taken as a subsystem of the *Performers System*. But there is no need for all performers to work at the same time. Fig.3 shows an example of the *Performers System*. The air-conditioner, electric window and electric curtain have the ability to adjust indoor temperature, and they are all connected to the home network. When adjusting indoor temperature, we could use the air-conditioner or the window and curtain, but not necessarily them all. The smart home system core is based on the home safety architecture introduced in [9].

The *Performers System* can adjust various physical properties of indoor environment by utilizing the functions the *performer*s provide. And this may involves different physical processes. E.g. indoor temperature adjustment through heat radiation or heat convection. Duration these processes, other physical properties may be affected, e.g. humidity and air speed.

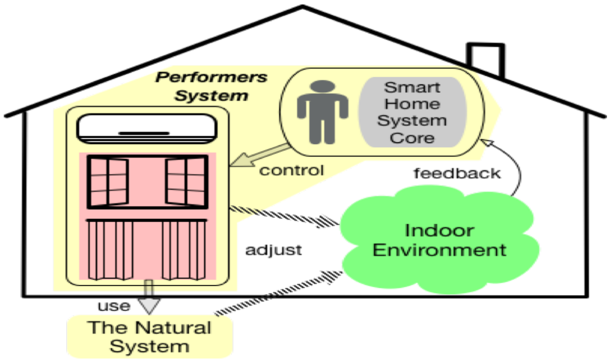

Fig. 3. An Example of the Performers System

B. Service

Definition 3 (Behavior of the Performers System): The way the *Performers System* behaves to adjust indoor environment.

For example, the *Performers System* in fig.3 has the ability to cool down indoor temperature. Its behavior is represented by the corresponding physical property variation, e.g. indoor temperature variation.

Definition 4 (Service): The behavior of the *Performers System* exhibits in order to fulfill occupant's comfort requirement.

Comfort means psychological and physical satisfaction with the state of the indoor environment, e.g. thermal comfort. It is the constraint on the behaviors of the *Performers System*. But the comfort is different under different conditions, e.g. temperature range for thermal comfort is different for different clothing, air speed, etc. conditions[10].

There are two ways to evaluate thermal comfort. The first is based on occupant's perception and manually set the desired temperature level. It is easy and accurate but limited by some scenarios. For example, the occupant can't spare a time to set indoor temperature because of busy doing something else. Or, For a baby or elder people, they may don't know how to set a temperature by using high-tech devices. The second way of evaluation is conducted by the smart home system core. Various heat index approaches are used to measure heat exposure in the literature[15]. They are usually calculated by temperature and humidity, etc. Among them there is a widely used one called PMV-PPD index[10]. PMV and PPD are short for predicted mean vote and predicted percentage of dissatisfied respectively. Six primary factors with respect to the environmental and personal information are considered. They are metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity. PMV and PPD are calculate by the following two formulas. Then combine with ASHRAE thermal sensation scale to determine the comfort.

$$PMV = TS \times (WM - HL1 - HL2 - HL3 - HL4 - HL5 - HL6) \tag{1}$$

where *TS* denotes thermal sensation transfer coefficient and is determined by metabolic rate. *MV* means internal heat production in the human body and is determined by metabolic rate and external work. *HL1*, *HL2*, *HL3*, *HL4*, *HL5* and *HL6* represents heat losses through skin, sweating, latent respiration, dry respiration, radiation and convection. The detail of these parameters are introduced in [10].

$$PPD = 100 - 95 \times e^{-0.03353 \times PMV^4 - 0.2179 \times PMV^2} \quad (2)$$

For environmental factors like humidity can be acquired through humidity sensors. For personal factors like metabolic rate, one can roughly evaluate according to occupant's activities, e.g. sedentary. Or take the advantage of wearable device to measure personal information, and send these data to the smart home system core to evaluate the comfort. But as far as the author know, cloth insulation cannot be evaluated by wearing wearable devices for now. It can only be roughly evaluated through scenarios like in hot summer, the value of cloth insulation is small and assign it an average value for summer season.

Definition 5 (Service Manner): The *service* under a specific condition is called a service manner.

For example, a sweating man in summer season need a cool indoor environment for comfort; a sedentary man in winter season need warm indoor environment. So, the conditions in the former example are high metabolic rate and high outdoor temperature, etc.; and low metabolic rate and low outdoor temperature etc. for the latter

Definition 6 (Critical Service Manner): The *service manner* in demand is called critical service manner.

In the above two examples, the cool indoor environment for comfort is the *critical service manner* for the sweating man; and the warm indoor temperature is the *critical service manner* for the sedentary man.

IV. Risk Model

A service delivery failure may result in hazardous situation and harm occupants. *Risk* has been defined as the combination of the likelihood of harm and the severity of that harm[8][11]. The risk model is used to model the mechanism of hazard formation and cause harm. It is based on the causality of event, which is shown in fig.4. The risk model can provide hazard formation information for prediction and evidence information relate to the hazardous situation for detection. And hazard reaction is based on the result of prediction, detection and the causes from hazard analysis by using the STAMP model and the *Performsers System*.

Definition 7 (Defect): Defects are the direct causes of a service failure.

For example, wrongly set heating mode of a *performer* in hot weather. The defects could come from the physical world or the cyber world or both; and they can be used to assist in precaution action. Plus the causes of precaution action failure (part of the hazard analysis based on the STAMP model) to assist in remedial action. Precaution action and remedial action will be introduced later.

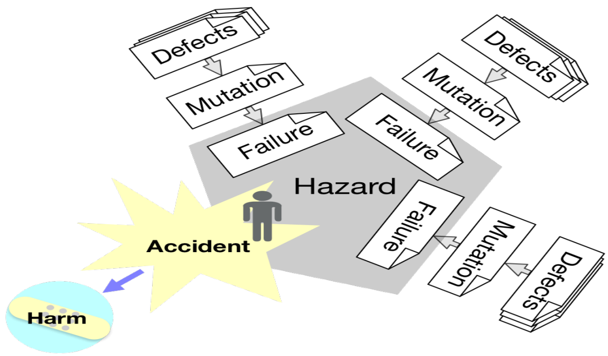

Fig. 4. The Risk Model

Definition 8 (Mutation): Mutation is the violation of constraint on the behavior of *Performers System*.

The constraint on the behavior of *Performers System* is to satisfy comfort purpose. Because the behavior is represented by the physical property variation, the constraint is the comfort definition on physical property variation. So, a mutation is that physical property variation deviate from the defined comfort. E.g. comfort interval for temperature variation can be calculated from the PMV-PPD index, if temperature variation deviated from the comfort interval, which means a mutation has happened. Or, if define comfort as the amplitude of temperature fluctuation should not exceed a value. A mutation in this case is the amplitude of temperature fluctuation exceed the predefined value.

Definition 9 (Service Failure): The behavior of the *Performers System* exhibits **failed** to fulfill occupant's comfort requirement.

It is occurred when a mutation has happened and there exist occupant(s) do perceived this uncomfortable the mutation brought about.

Definition 10 (Hazard): It is an indoor environment state that has a possibility to harm occupant.

One or more service failures violate safety constraint may form a hazardous situation that can result in accident and cause harm to occupants. The safety constraint is the constraint on physical property variation by concerning not harm occupants. E.g. in order to not cause heat stroke, indoor temperature should not exceed a threshold value.

To evaluate a hazard, one can use for example heat stress [16] to estimate whether a heat disease would happen. *Heat stress* is the sum of the heat generated in the body plus the heat gained from the environment minus the heat lost from the body to the environment. It involves environmental factors, e.g. humidity, and metabolic heat. And metabolic heat can be estimated based on occupant's activity or measured by wearing wearable device.

Definition 11 (Accident): It is an unintentional event that a *hazard* result in harm occupant.

It is a state involving both indoor environment and occupant, which a hazard is harming occupant or has harmed occupant. Still take the heat disease example, to evaluate an accident by evaluating the hazard and using heat strain to evaluate the body's response to heat stress[16]. Parameters like body temperature, metabolic rate can be measured by wearing wearable device.

*Mutation*s and *hazard*s provide detectable evidence for service failure and hazard **detection**; The way a service may fail and hazard can occur provide pattern information(chains of events and related evidence information) for hazard **prediction**. By using the proposed *Performers System* and the STAMP model to analyze the identified *hazard* for *defect*s. Then if a *service failure* is detected, **precaution reaction** relate to the *defect*s is required; if a *hazard* is detected, **remedial reaction** relate to the *defect*s is required.

The purpose of *precaution reaction* is to restore service delivery. It involves reconfiguration of the *Performers System*. The reconfiguration has two meanings, one is reset the current working performers, the second is to take the advantage of ready-to-use performers to achieve the restoration. The purpose of *remedial reaction* is to restore a safe indoor environment state, no matter a *service failure* (need precaution reaction in this case) or normal *service* delivery. It also involves reconfiguration of the *Performers System* and the meaning is the same as discussed above. *Remedial reaction* has another content that *precaution reaction* don't have – a **warning mechanism**. The warning mechanism is triggered when a *hazard* is forming or has formed, which means the precaution reaction has failed and the reconfiguration stage of remedial reaction is currently executing. And it has two levels, the first level is to warn the occupant. At this stage, the harm is not that severe and the occupant may not need a medic. The second level is for a much more urgent situation that the occupant need a medic. The warning mechanism informs an emergency department, e.g. a hospital or ambulance, through the network that connecting to a medical system.

V. Conclusion

This paper first proposed the concept of the *Performers System* in order to apply the STAMP model for hazard analysis. Then based on the *Performers System* the *risk model* is given, which can provide detectable evidence of *service failure* and hazard information for detection. The hazard formation pattern information can be used for prediction. Finally reaction including precaution reaction and remedial reaction that take the advantage of the result from detection, prediction and causes of identified hazard to restore a comfort and safe indoor environment.

The relationship among the defined terms can be seen from fig.5. *Defect* originate from the *Performers System* and the natural system. *Mutation* comes from the violation of comfort constraint on indoor environment. These dotted lines representing the connected terms has relation in their definition.

Typical examples with respect to indoor temperature are used to demonstrate the appropriateness of the propositions and related definitions.

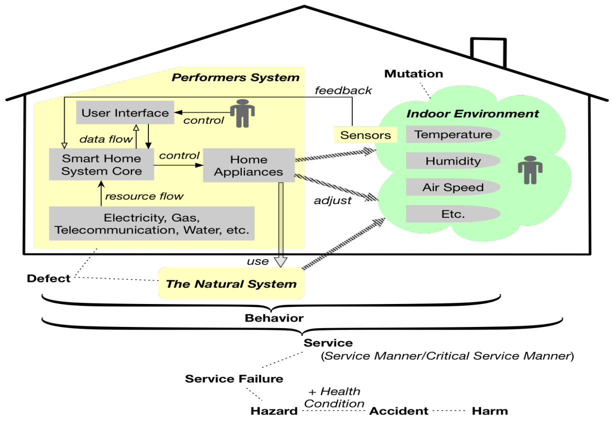

Fig. 5. Terms Relationship

For future works, in order to evaluate the propositions in this paper. First, identify a safety problem, e.g. heat stroke. Then setup an example *Performers System* and use the STAMP model for hazard analysis. Second, implement the prediction and detection mechanism, then the reaction strategy. Last, acquire data for analysis. Some of these work is in progress the time writing this paper.

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