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DOI
10.3233/JID190004

Publication date
2020

Document Version
Accepted author manuscript

Published in
Journal of Integrated Design and Process Science

Transactions of the SDPS:
Journal of Integrated Design and Process Science
XX (2019) XX-XX
DOI 10.3233/jid-201x-xxxx
http://www.sdpsnet.org

Personalized Messaging based on Dynamic Context Assessment: Application in an Informing Cyber-Physical System

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Abstract Hazard-intense applications of cyber-physical systems (CPSs) such as the evacuation of a building on fire requires optimal management of stakeholders. Personalized message generation and informing of stakeholders based on real-time assessment of the dynamic context of stakeholders is the research and engineering challenge addressed by this paper. Personalized multi-message construction mechanism (MCM) that is enabled by dynamic context modeling, inferring and reasoning is proposed. Dynamic personal context was defined as the total of space- and time-varying situations that are relevant to a stakeholder. The basis of generating messages is a quantitative evaluation of the implications of the relevant situations with regards to the target stakeholders. The concept of impact indicator was used to represent the implications of situations and a personal danger level indicator was used to choose a proper message template for message construction. The algorithms included in the MCM were validated in a (simulated) indoor fire evacuation guiding application. Test people were involved in the practical evaluation of the quality of the generated messages. The conclusion is that the proposed MCM provides more sufficient information about personal context and expected actions than the messages constructed based on static context information.

Keywords: Informing Cyber-Physical Systems, Dynamic Context Information, Context Awareness, Personalized Message Construction, Guiding Indoor Fire Evacuation.

1. Introduction

Cyber-physical systems (CPSs) represent a new generation of systems which offers new affordances for satisfying novel societal needs and or providing sophisticated resources and services (Horváth *et al.*, 2017). Considering their initial conceptualization, the paradigm of CPSs is rapidly advancing from both theoretical and practical perspectives (Baheti & Gill, 2011). The advanced computation, communication, and control technologies, which were characteristics of their first generation, have been extended with context management, reasoning, planning and adapting capabilities. These enable the second generation of CPSs (2G-CPSs) to operate as smart single- or multi-actor type systems. The latter systems can be

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configured in various arrangement according to the tasks they are supposed to complete. 2G-CPSs will be able to combine building self-awareness and reasoning towards self-adaptation, and to act in an anticipating or proactive manner even in varying contexts (Tavčar & Horváth, 2018).

Informing cyber-physical systems (I-CPSs) are seen as a specific cluster of 2G-CPSs together with the complementing transforming CPSs (such as a smart cyber-physical manufacturing system). Their smart operation is focused on providing informational services for applications and stakeholders. The possible range of informational services is rather broad (including, e.g. customized action plans, timely-refreshed information, or context-sensitive guidance). Actually, the variety of application opportunities for these systems is constrained only by the imagination of the system designs and by the economics of implementing them for various applications. Usually, the control functionality of I-CPS is extended with data analytics functionality, which is based on multiplexed sensor nodes and pervasive sensor networks, and information modality transformers and message generators. As reported in the literature, typical examples are distributed tourist information systems (Osborn & Hinze, 2014), context-aware navigation systems (Saeedi *et al.*, 2014), healthcare recommendation systems (Shojanoori *et al.*, 2012), patient context monitoring systems (Kataria *et al.*, 2008), and evacuation management systems (Ibrahim *et al.*, 2016). The servicing activities of I-CPSs include various messaging functions such as: (i) selecting informing modality, (ii) constructing personalized messages, and (iii) distributing messages to the stakeholders.

I-CPSs are supposed to execute messaging operations according to the actual situational context that gives the reference for interpretation of messages and completing actions. Towards this end, two types of messages are normally used in I-CPSs, namely, instructive messages and informative messages. Instructive messages are used to inform stakeholders about "what they should do" and these may manifest as personal recommendations, situated solutions, or action guidance. Informative messages indicate "what the stakeholder should be aware of". These messages are intended to increase the situational awareness of the stakeholder (or in other words, "of what is happening around the stakeholder"). Both types of messages are to be based on a factual description and 'understanding' of the situation or circumstances that are relevant to individual stakeholders. Message generation has both syntactic and semantic aspects. The former is related to information engineering, while the latter is associated with language processing. This gives an interdisciplinary flavor the messaging in I-CPSs.

Ultimately, the objective of dynamic context processing is to support the decision-making process of the stakeholders in cases such as hazardous events (evacuation scenarios) or mission-critical applications. Therefore, the messages constructed for stakeholders should (i) be sensitive and tailored to dynamically changing contexts, and (ii) include both descriptive information about the situation the stakeholders are in (or might be troubled with) and instructive information to command or assist their actions. Although many computational message construction mechanisms were developed, most of them consider only static context information, e.g. weather, temperature, daytime or permanent things of a particular location, so as discussed in (Wu et al., 2016), (Lehsten *et al.*, 2014) and (Braunhofer et al., 2013). However, the objective of this paper is to propose a real-time message construction mechanism (MCM) that generates both informative and instructive messages based on a real-time processing of dynamic context information.

The rest of this paper is structured as follows: Section 2 presents an overview and concludes about the related research and results. Section 3 discusses the foundational concepts and computational elements of the real-time message construction mechanism. Section 4 presents the testing of the algorithms included in the proposed MCM in a simulated application case. The objective is to validate the functionality and usability of the MCM as the messaging unit of an indoor fire evacuation guiding system. Section 5 reflects on the whole of the work, concludes about the results and the observations, and gives a concise overview of future research opportunities.

2. Related work and results

2.1 Context-Dependent Generation of Natural Language Texts

Text generation is a subfield of natural language processing. Based on the knowledge of computational linguistics and artificial intelligence, it synthesizes texts in natural languages to satisfy certain communication requirements (Zhang & Sun, 2009). Most of the existing context-dependent text generation systems are designed with the assumption of using template-based generators. An example of text generation systems is the shopping assistant system (ISAS) that is able to plan a route within a shopping mall for users who want to buy products according to their shopping list (Wu, et al., 2016). Reported in (Braunhofer, et al., 2013), the context-aware recommender systems (CARS) provides information to users concerning weather conditions or the nearby surroundings depending on the location of the users. In this line of systems, we should mention the context-aware tourist informing system (CATIS), which provides information to the users based on location, time of day, speed, the direction of travel, personal references, and device type (Pashtan et al., 2003). A location-based recommendation system was proposed by Bagci & Karagoz (2016) that generates a list of locations for the user to visit and supports social networking of the user. In these and many other applications, the personal situational context of the user is considered at the generation of the personalized text. The personal context may include the existing social relations, personal preferences, and current location. Most of the template-based generators reported in the literature are domain-dependent. Location of the user is normally considered as the condition for determining the relevant content. The main drawback of template-based text generators is the need to create, maintain and update templates for the use in multiple applications.

Another approach to text generation is natural language generation (NLG) that employs a pipelined architecture (or consensus architecture) (Reiter, 1994) (Mellish et al., 2006). Many model-based, context-aware NLG systems were reported in the last years. To address the problem of contextual relevance in the generation of news comments, Zheng et al. (2017) proposed a gated attention mechanism to self-adaptively and selectively use news context. Tang et al. (2016) proposed a context-aware approach, which encodes the contexts into a continuous semantic representation and decodes the semantic representation into text sequences with recurrent neural networks. To generate human-like sentences in question answering systems, Zhou. et al. (2016) proposed a context-aware long short-term memory network model for NLG, which was a data-driven approach to generate text based on the question to be answered, semantic values to be addressed in the response, and the dialogue act type during the interaction. The existing context-aware approach for text generation considers textual context. They are suitable for correcting the semantics of messages to a grammatically correct sentence. In addition, most of the approaches employ a natural network to generate a word at a time, which cannot be used when multiple aspects of user context are to be taken into consideration simultaneously, not to mention the case when their cardinality increases in various situations.

Compared to model-based approaches, template-based approaches are more suitable for real time generation of personalized messages about the dynamic context of users. They are able to handle multiple aspects of time-varying scenarios. Templates provide dependent structures for the messages, which reduces the time needed for message generation and help to increase the relevance and specificity of message content. The text embedded in messages and the situations happening around users could be bridged through predefining various messages components used to describe the situations. It means that when the context of users is changed, new messages components could be changed for messages construction easily. However, the existing template-based approaches only consider the static context of users and thus the content of the generated messages cannot adapt to the emerging situations around the users.

2.2 Context-Dependent Distribution of Messages

At designing informing systems, both the possible low bandwidth of communications and the possible limited attention of the users should be addressed. In addition, the principles of message distribution and the modality of the constructed personal messages should be considered. Giving attention to these, the efficiency of message transfer and informing can be increased, respectively. Therefore, the computational and system functions related context-aware messaging have attracted the interest of many researchers. For instance, Nakanishi et al. (2000) proposed a context-aware messaging system, which is able to redirect the incoming e-mails or telephone calls according to the schedule and location of the users and the media available for them. Knox et al. (2007) and Knox et al. (2008) proposed a context-aware message forwarding platform, which is able to send certain incoming e-mails to users based on their changing situations and shifting priorities. The context of the users' routine is derived by tracking their location and monitoring their (next) daily schedule. Pinto et al. (2012) proposed a context-aware architecture to capture context information of users and to control multimedia channels (e.g. unicast, multicast or broadcast channels) for message delivery. The proposed architecture supports efficient and sophisticated content sharing within mobile communities. The aim of the European FP7 Context Casting (C-CAST) project was to optimize the delivery of personalized session contents to multiple mobile users based on the context information (Coutinho et al., 2010). In this project, a software architecture was developed for delivering multiparty services. The proposed solution has the capability of performing required adaptations on the session, transport, and network levels of interoperation, triggered by context changes such as events, locations or a deterioration of network condition.

In informing systems, the communication modalities can be either of human-to-human types, e.g. face-to-face, voice-only, linked teletypes, and interactive handwriting (Ochsman & Chapanis, 1974), or of machine-to-human types, e.g. graphical modality, voice modality, or textual modality (Cohen & Oviatt, 1995). Human-to-human modalities are rarely considered in I-CPSs, while machine-to-human interfaces are more widespread. Various context-aware machine-to-human interfaces were designed to support the deployment of informing services for the users. If proper modalities are selected for informing actions based on the context or situation of the users, then interfaces can have a large influence on attracting users' attention. Zaguia et al. (2010) proposed a context-aware system, which allows users to access ubiquitous web services, through a suitable modality. In their work, context information was considered as a combination of the situational context of the user, his environment, and his computing system. As an outcome of the research of Ghorbel et al. (2006), an assistive service provision architecture was proposed. Based on processing context information (such as user profile, environment context, and end-user terminal), this supports providing assistive services to dependent people (elderly and people with disabilities). Gouin-Vallerand et al. (2013) proposed a context-aware service provisioning mechanism, which allows the concerned informing systems to adapt the interaction modalities according to contextual information such as user profiles, device profiles, software profiles, and environment topology.

It can be seen from the related work that modality of distribution of personalized messages can increase the efficiency of message transfer and informing. Several aspects have been considered, including (i) available channels for delivering messages, (ii) proper devices that are interacting with stakeholders and (iii) suitable modalities for representing the messages. In addition, adaptive and customized distribution of messages has been realized considering context-dependency of modality. Message distribution strategies based on static context information cannot satisfy the requirements for hazard-intense I-CPS applications properly, where personal context is heterogeneous, unstructured and may change rapidly. Therefore, a sophisticated solution for handling dynamic context of stakeholders is needed.

2.3 Major Findings of the Literature Study

As indicated by subsection 2.1, two characteristic strands can be identified in the current literature of messaging, namely: (i) context-dependent generation of natural language texts and (ii) context-dependent distribution of messages. Although the need for context-aware software capabilities is recognized in various application fields, the phenomenon of contextualized communication between informing systems and human stakeholders has only been superficially addressed so far. Many white spots can still be found in the field of CPSs, in particular in the subfield of aware and adaptive smart

CPSs. Proposals and solutions for message generation on natural language and messaging in dynamic contexts by CPSs are also scarce. The overwhelming majority of existing computational mechanisms considers static context information only. The progress with reasoning with dynamically changing context information in real-time is still limited. With regards to the stakeholder to be informed, processing dynamic context information is restricted to location changes or daytime changes. However, personal context modeling should include not only the specific personal information of the target stakeholder but also information about the state and activities of other relevant entities and the surroundings.

Context information is normally considered as descriptive attributes of the stakeholders and stored as various profiles in the existing adaptive interaction modality systems. This type of systems has limited capabilities to deal with situations when the actual context in real-life scenarios does not accord with the context information stored in the profiles, e.g. a stakeholder uses the device of another stakeholder. Several similar cases can be foreseen when dynamically changing situations, rather than steady-state situations, are to be dealt with. Therefore, researchers need to provide adequate theoretical fundamentals and computational methodologies for processing dynamic context information. This issue should be addressed not only in research but should also be considered in the development of upcoming systems, which are supposed to adapt themselves to changes as these appear in varied forms in real-life application cases. The issue derived from the low communication bandwidth requires using a prioritizing algorithm in the future systems. This algorithm may treat stakeholders differently, for instance, in the case of interacting with a great number of stakeholders in emergency situations. Below, a novel and effective context-dependent message construction mechanism is discussed that was developed to address the mentioned issues.

3. A Context-Dependent Message Construction Mechanism

3.1 Fundamentals of the MCM

In our previous work, we proposed a representation scheme (namely, the spatial feature representation (SFR)-matrix) for dynamic context information management and computation (Horváth et al., 2016). The personal context of a stakeholder was defined as the total of the information characterizing the associated varying situations. The SFR-matrix is based on a relatively simple underlying (relational) logic and facilitates collecting information about situations. It supports building awareness based on the captured dynamic context information. It also supports generating additional descriptive information (e.g. location, attributes and time of happening) of situations that may be identified in a given context. The built (situational) awareness and the derived additional descriptive information were taken into consideration as the factual basis of the MCM. As discussed below, we employed a quantitative approach in the proposed MCM to compute the situations relevant to a stakeholder and to convert the information related to a situation to informative and instructive messages.

The context-dependent MCM is part of a multi-module computational platform, which can provide real-time dynamic context computational services for I-CPSs. The overall architecture and workflow of this platform is shown in Fig. 1. It contains four major modules, which include multiple algorithms for (i) representing and modeling of dynamic context of entities, (ii) building awareness in dynamic context, (iii) deriving action plans for entities, and (iv) constructing personalized messages depending on the dynamic context of entities. The MCM is an output generator module of the computational platform, which eventually manifests as an integrated software platform. The awareness-building module, the reasoning module, and the message construction module of the platform are procedurally interconnected. This interconnection means that the computation should be completed in the former modules before the turn of the latter modules since their outcome is used as input in a latter computational module.

One input of the MCM is the complex data structure that captures dynamic context information. The platform processes all pieces of data concerning the physical entities and their relations that are needed to describe the momentary states of the related processes (e.g. the attributes or the location of an entity at a given point in time). The actual variations of the physical process can be inferred from the temporal

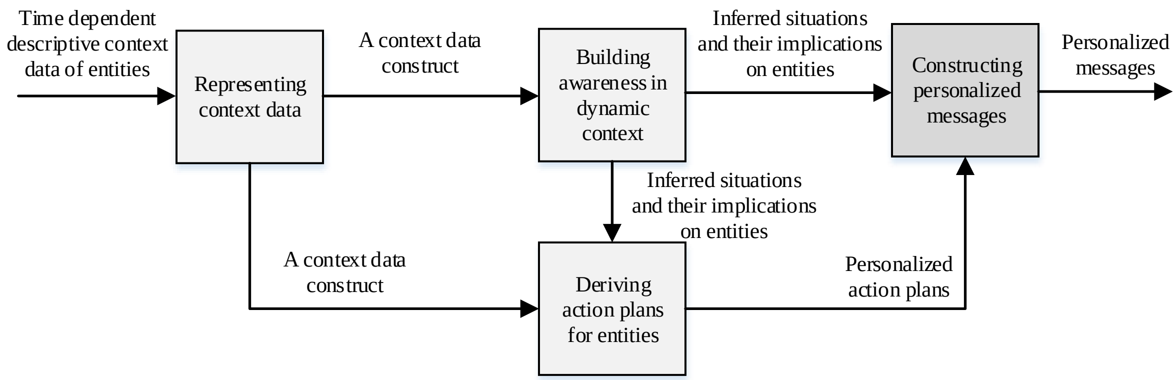

Fig. 1. The generic framework of the computational platform for dynamic context computation

relations of the momentary states. The variations of the states of entities are captured for computations as events. An event is a change over a predefined period of time (referred to as a time increment in computation). An event may mean changes, among others, in the location, attributes, and relations of entities during a given time increment. Multiple interacting events form a situation, which is one higher level computational abstraction. The concept of the situation was introduced to be able to describe a phenomenon, which happens in a duration of time (possibly, over multiple computational time increments). A situation can be inferred by integrating and abstracting information about multiple states and/or events according to certain predefined rules. For instance, a people jam can be defined based on the states and/or events related to several stakeholders present at a location. In a physical process, a situation may change in terms of its location and/or attributes. Multiple correlated and interplaying situations form a scene, which describes the state of the local world considered in dynamic context calculation. The identified situations, the changes of the situations and the implications of their interplay were considered as one of the inputs of the MCM.

Another input of the MCM is the personalized action plans generated for individual stakeholders. Every action plan contains a series of actions that are supposed to be performed by the informed stakeholder. Generation of the personalized action plans considers the inferred situations and their implications on the individual entities and the capabilities of the entities. For instance, in the case of indoor fire, the action plans refer to the escape routes that are to be followed by the informed stakeholders. Generation of the escape routes depends on the inferred situations happening in the environment (e.g. people jams and fires) implications of the situation and the attributes of stakeholders (e.g. age, handicapped or not).

Due to the limitation with the length of this paper, technical details with regard to inferring situations and their implications, and generation of personalized action plans will not be included. It was assumed that these two types of knowledge were already known before the MCM started to work. Accordingly, the specific objective of the MCM is to make use of the inferred situations and their implications, and the developed action plans to construct personalized messages that support the communications to the stakeholders. To achieve this, the main technical requirements of the context-dependent MCM have been specified as follows:

- The MCM should judge the relevance of the inferred situation(s) around a concerned stakeholder. And, the most relevant situation should be selected to inform the stakeholder.
- When a situation is selected for constructing messages, the information describing the situation (e.g. location, attributes and time of happening) should be included in the informative message.
- An overall evaluation of the personal danger level of stakeholders should be achieved concerning the implications of the situations that are relevant to the individual stakeholders.

- The concerned stakeholders should be ranked according to the calculated personal danger level in order to prioritize the informing services for the stakeholders in danger.
- A proper way of rhetoric should be applied for sentence construction, which implies the evaluated personal danger level (e.g. dangerous or safe).
- The content of the personalized message should have a strong correlation with the present context of the concerned stakeholders. It requires a near real-time message construction.

These six requirements can be interpreted by the following example: in case of indoor fire, the stakeholders in the burning building should be informed with informative messages about situations happening around and the instructive messages about the actions to be taken for escaping from the building. Typical situations in this scenario are (i) fire and (ii) people jams. To construct informative messages, the informing system should first calculate the relevance of the inferred situations to individual stakeholders and inform individual stakeholders about the situation that is the most relevant to him/her. This should consider the attributes of the situations and individual stakeholders, as well as the spatial and temporal relations between them. For instance, although fire has a bigger threat than people jam in nature, the relevance of a people jam to the stakeholder at a given point in time might be higher than the fire to the same, if the fire is far away from the stakeholder and the is involved in the people jam. In addition, calculation of the personal danger level enables treating stakeholders differently. To construct personalized messages, the most relevant situation to a stakeholder and the generated action plans can be described with a proper way of rhetoric, reflecting how dangerous the personal context of the stakeholder is. For instance, if the stakeholder is in danger, a pressing style of wording could be used in the construction of messages. Furthermore, the message construction and sending should happen in a real-time manner to avoid any miscommunication cases, e.g. informing the stakeholder about a people jam that has disappeared.

3.2 The Message Construction Mechanism

Based on the requirements, the computational mechanism used to construct personalized messages is shown in Fig. 2. The MCM contains several sequential computational functions. The computational principles of each function are illustrated as follows. When situations and their implications on entities are inferred out, the first function was used to calculate the relevance of all situations to individual entities. Normally, a situation only contains several entities (e.g. a people jam), while the rest of the entities are not included. It means that the situation has a direct impact on the entities involved in the situation and has an indirect impact on the rest of the entities. The extent of the impact of a situation on an entity is the basis for calculating the relevance. To quantitatively calculate the relevance of a situation, the concept of impact indicator was used. The general term “impact” was considered to indicate either the actual impact that a situation hampers the entity (e.g. a people jam slows the motion of a person) or the potential influence of a situation that the entity might be involved in (e.g. a stakeholder will be troubled by the fire).

The impact indicator, $II_{ij}(t)$, of a situation, s_i, on an entity, ε_j, is calculated as:

$$II_{ij} = \begin{cases} \dfrac{1}{\Delta t_{ij} D_{ij}} IC_i, & Indirect\ impact \\ IC_i, & Direct\ impact \end{cases} \tag{1}$$

where: IC_i is the impact coefficient used to represent the implication of situation, s_i, on the entities involved in the situation. It can be either predefined or calculated based on the attributes of the situation and the entity using the formula $-1 \leq IC_i < 0$. For instance, in the case of an indoor fire, the impact coefficient of a people jam with 10 people can be -0.1, while for a people jam with 30 people it can be -0.2, and -1 for the fire. The different values of IC_i indicate the quantitatively specified implication of the considered situations on the entities involved. In the previously mentioned example, the actual value of IC of the fire is set to -1, since stakeholders may lose their life when involved in fire. In the above evaluation of the indirect impact, Δt_{ij} is the time difference between the point in time when s_i happens and the point

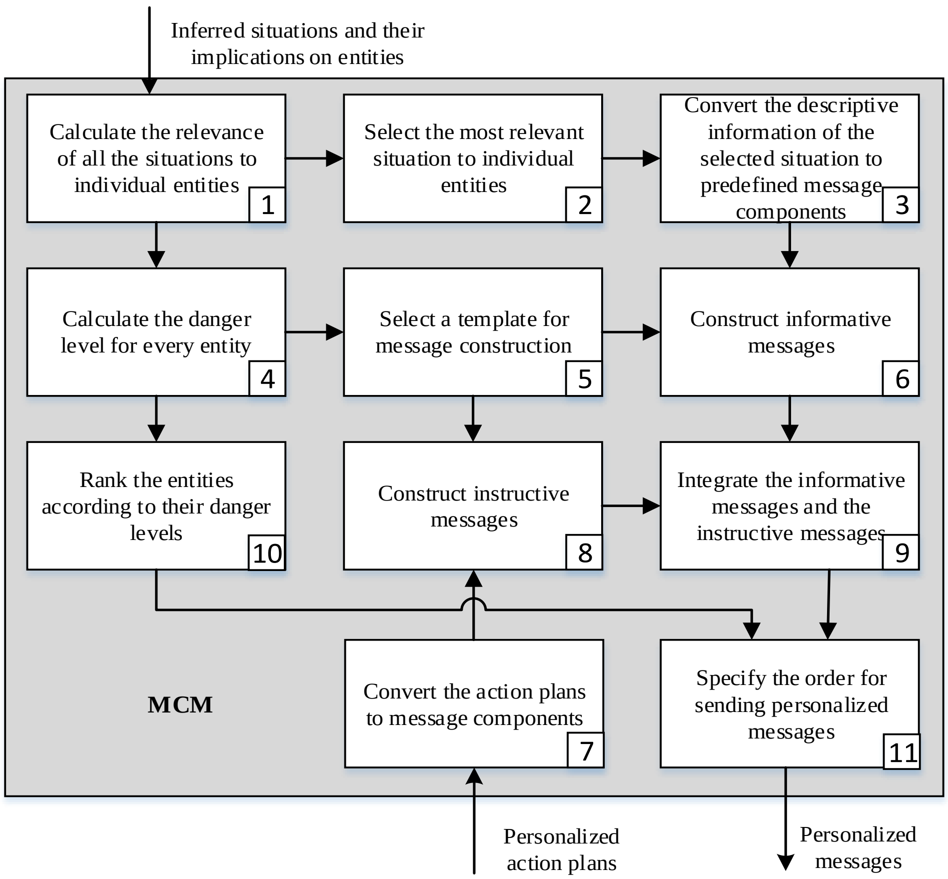

Fig. 2. The dynamic context-dependent message construction mechanism.

in time when ε_j is considered. D_{ij} is the distance between the location where s_i happens and the location where ε_j is at the considered point in time.

After calculating the impact indicators of all situations, the relevance of situations to individual entities can be determined. For instance, if a situation has a higher impact indicator on an entity, the situation is more relevant to the same. According to this principle, the second function selects the most relevant situation to individual entities. Then, the descriptive information of the selected situation should be converted to various message components (e.g. words or phrases) in the third function. A library of alternative message components should be pre-defined to enable the converting. For instance, the location of a situation can be converted to the name of the room in a building where the situation happens. In addition, based on the calculated impact indicators of situations, the danger level of every entity can be carried out. This refers to an overall consideration of the personal context. Towards this end, the sum of the impact indicator (SII) of situations related to individual entities is calculated, which can be noted as:

$$SII_{s_j} = \sum_{i=1}^{n} II_{ij} \tag{2}$$

where: II_{ij} is the impact indicator of a situation, ε_i, on an entity, s_j. Assumed is that there may be n situations in total associated with the entity at a given point in time.

Since the SII is a reference for quantitative evaluation of the personal context, the SII can be used to judge if the stakeholder is in danger or not. In this way, personal danger level of entities can be calculated based on several application-dependent thresholds in the fourth function. Then, message templates can be selected based on the calculated personal danger level in the fifth function. For instance, when a concerned stakeholder is in a dangerous situation, a message template with an emergent style might be used to construct the sentences. Therefore, based on the message components generated from the third function and the selected message templates, informative messages can be generated, which is done in the sixth function.

The derived personal action plans, which are another input of the MCM, can be converted to various messages components in the seventh function. For instance, the route for escaping from a burning building can be converted to a series of messages components indicating the target locations included in the route. Then, the selected message template was used for constructing instructive messages in the eighth function. After this, the constructed informative messages and instructive messages are integrated to form the personalized messages for communication with the target entities. Furthermore, based on the calculated SII of entities, the entities can be ranked into a list according to their personal danger levels. This is completed in the tenth function. According to the list, the MCM is able to specify the order for sending the constructed messages to the personal devices (e.g. mobile phone) of the concerned entities for informing, which is decided in the last function in the MCM.

3.3 Implementation of the MCM

The designed MCM was implemented and the algorithmic workflow of the implemented prototype is shown in Fig.3. The inputs of the prototype implementation of the MCM are: (i) a list of entities with their attributes, (ii) inferred situations, (iii) implications of inferred situations, (iii) a library of message components, (iv) a set of message templates, (v) personal action plans, which are generated according to the objective of the system and the need of the entities. The output of the prototype is the generated personalized messages.

When an entity is selected from the entity list, first the prototype judges if the entity can be informed, or not. The informability of an entity is considered as one of the attributes of the entity, and it can be decided based on the status of the informing terminal owned by the entity. If the selected entity can be informed, then it is sensible to construct personalized messages. The (computational) principles for calculating the impact indicators of situations are presented in Section 3.2. The impact coefficient of a situation is an application-dependent value, which should be specified by the application designers.

For each concerned entity, the situation that is characterized by the largest impact indicator is selected and the spatial, attributive and temporal (S.A.T.) data describing the situation are converted into alternative message components (i.e. words and phrases). Table 1 shows a sample set of rules designed for lexicalization of the

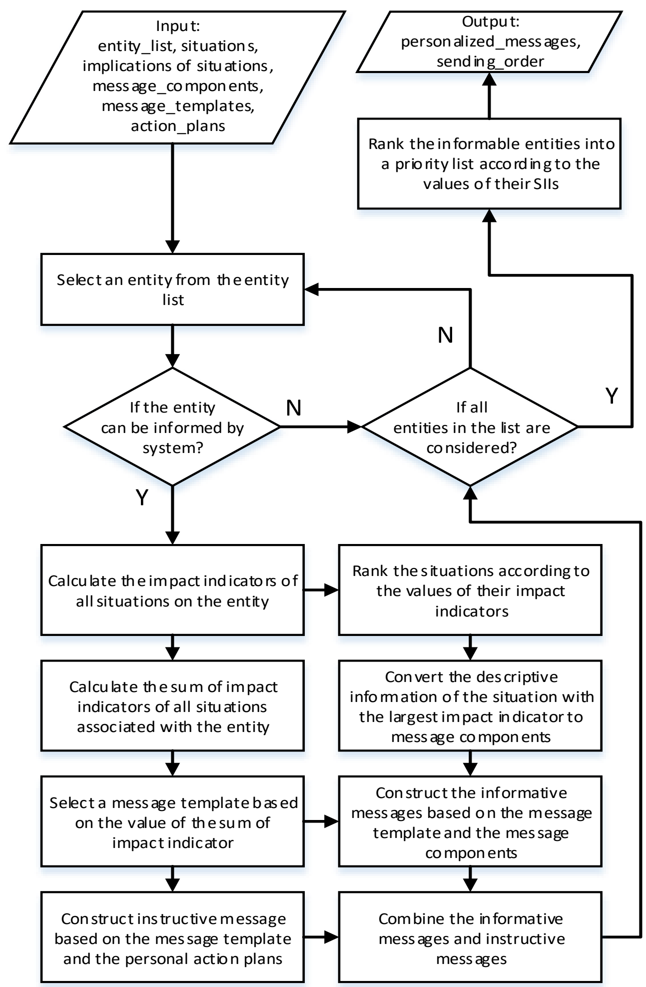

Fig. 3. The workflow implemented for constructing personalized messages

Table 1 Lexicalization of S.A.T. information describing a situation

Type of information	Category	Conditions	Referred message components
Spatial information of a situation	Static: distance	$\text{dis}_{ij} \geq d_{vl}$	Very far away from
		$d_l \leq \text{dis}_{ij} < d_{vl}$	Far away from
		$d_s \leq \text{dis}_{ij} < d_l$	Close to
		$0 \leq \text{dis}_{ij} < d_s$	Very close to
	Dynamic: change of distance	$\Delta\text{dis}_{ij} \geq d_{ff}$	Fast away from
		$0 \leq \Delta\text{dis}_{ij} < d_{sf}$	Slowly away from
		$d_{sa} \leq \Delta\text{dis}_{ij} < 0$	Slowly towards
		$d_{sa} > \Delta\text{dis}_{ij}$	Fast towards
Attributive information of a situation	Static: speed of motion	$speed > s_f$	Fast
		$s_s < speed < s_f$	Mediate
		$s_s > speed$	Slow
	Dynamic: change of speed of motion	$\Delta speed > cs_i$	Speed increases
		$cs_d < \Delta speed < cs_i$	Speed is stable
		$cs_d > \Delta speed$	Speed decreases
Temporal information of a situation	Static: time of happening	$t_s(DS) - t_c \geq t_{ff}$	Far future
		$t_{nf} \leq t_s(DS) - t_c < t_{ff}$	Near future
		$t_n \leq t_s(DS) - t_c < t_{nf}$	Nearby
		$0 \leq t_s(DS) - t_c < t_n$	Now
		$t_c \leq t_s(DS) - t_c < 0$	Recent
		$t_{np} \leq t_s(DS) - t_c < t_c$	Near past
		$t_{fp} \leq t_s(DS) - t_c < t_{np}$	Far past
	Dynamic: variation of happening time	$\Delta t_s(DS) > 0$	Later
		$\Delta t_s(DS) < 0$	Earlier

S.A.T. information of a situation. Based on the rules, proper message components can be specified by comparing the relevant values of the S.A.T. data of the concerned situation with the predefined threshold values. An example of converting the specific descriptive information of a situation to alternative message components by applying the specified rules is presented in Fig. 4.

As a next computational task, the SIIs of the concerned entities should be calculated, which are regarded as a reference for selecting a message template. The template-based approach was considered

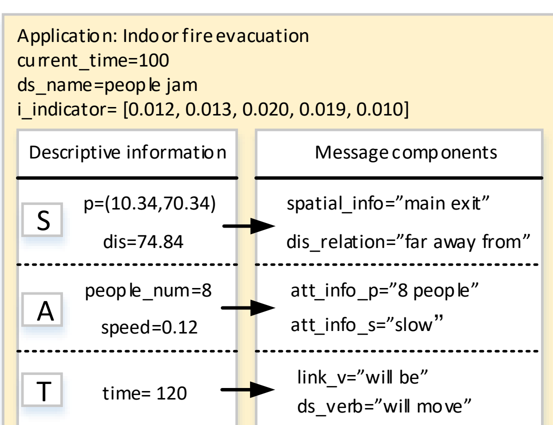

Fig. 4. An example of converting information of a situation into various message components.

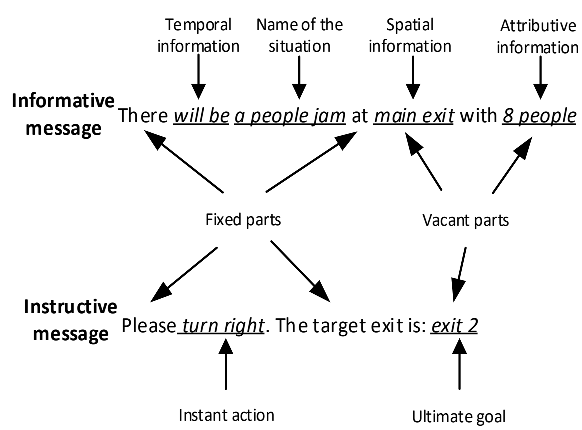

Fig. 5. Construction of personalized messages based on a message template.

for message construction since it provides a simple and fast way for real-time construction of natural language texts in different conditions. Towards this end, various message templates should be articulated and stored in a warehouse for the MCM. An example of a typical message template is shown in Fig. 5.

The principles for designing messages templates are presented as follows. Firstly, every message template includes fixed parts and variable (vacant) parts. In the process of constructing messages, the generated message components are placed on the vacant places according to the type of information they represent. The fixed parts serve as the linking words among the vacant parts, make a sentence readable, and express different rhetorical styles, e.g. prepositions and modal particles. Secondly, every message template for constructing informative messages should include some places showing the name and S.A.T. information describing the concerned situation. To facilitate the construction of instructive messages, the recommended action plans include both the instance actions that the entity should follow at the present time and the ultimate goal of the entity.

When the message components are filled into the selected message template properly, the informative and instructive messages are integrated to form a personalized message for the concerned entity. When all entities in the entity list have been considered, the informable entities should be ranked into a priority list according to their SIIs. The generated priority list and the personalized messages are the output of the prototype implementation of the MCM. This output is used as a basis for providing message generation services for and to perform informing operations by the I-CPS application embedding the computational platform for dynamic context computation.

4. Validation of the Proposed MCM

The usability of the proposed MCM was tested in a simulated scenario: an indoor fire evacuation. The implemented prototype was assumed to provide messaging services for an I-CPS, which controls the process of evacuation. This experimental system is referred to as indoor fire evacuation guiding (IFEG) system. In this section, the background of this application, the fundamental setup of the simulation, and the details of simulation are presented. The validation involved a comparative study concerning the assessment of the results of the dynamic context computation enabled MCM and an approach which controlled the evacuation based on only static context information. The quality of the generated messages was evaluated by human stakeholders.

4.1 Description of the application case

In case of indoor fire, the practical issues to be considered are: (i) the stakeholders need information concerning the danger, which makes them aware of their actual situation, and (ii) the optimal route for a stakeholder is not always the shortest path, since it may be occupied by fire or taken by a people jam at certain point in time (currently or in the near future). The objective of the IFEG system is to provide personalized messages to the stakeholders (escapers and firemen) in a burning building to support the evacuation of all the escapers safely. Therefore, both informative and instructive messages should be generated and delivered in the right time to the stakeholders. If we assume that all pieces of information related to the varying event scenario can be aggregated properly, the IFEG system should (i) smartly handle the dynamically changing context of stakeholders, (ii) develop individualized solutions (action plans) based on context-based reasoning operations, and (iii) generate proper personalized messages for communication. In the following part of this section, the generation of personalized messages for the IFEG system and the perceived value of these messages are assessed.

4.2 Simulation of the application case

To simulate a real-life indoor fire scenario, the following environment set up was implemented in MatLab®: The ground floor of the Building IDE of TU Delft (Fig. 6(a)) was digitally modelled by a 2D space (Fig. 6(b)). Its size was 130m*100m. The initialized situation involved 80 stakeholders (represented by circles and diamonds in Fig. 6(b)), 4 exits (represented by solid cubes in Fig. 6(b)), and a location of a

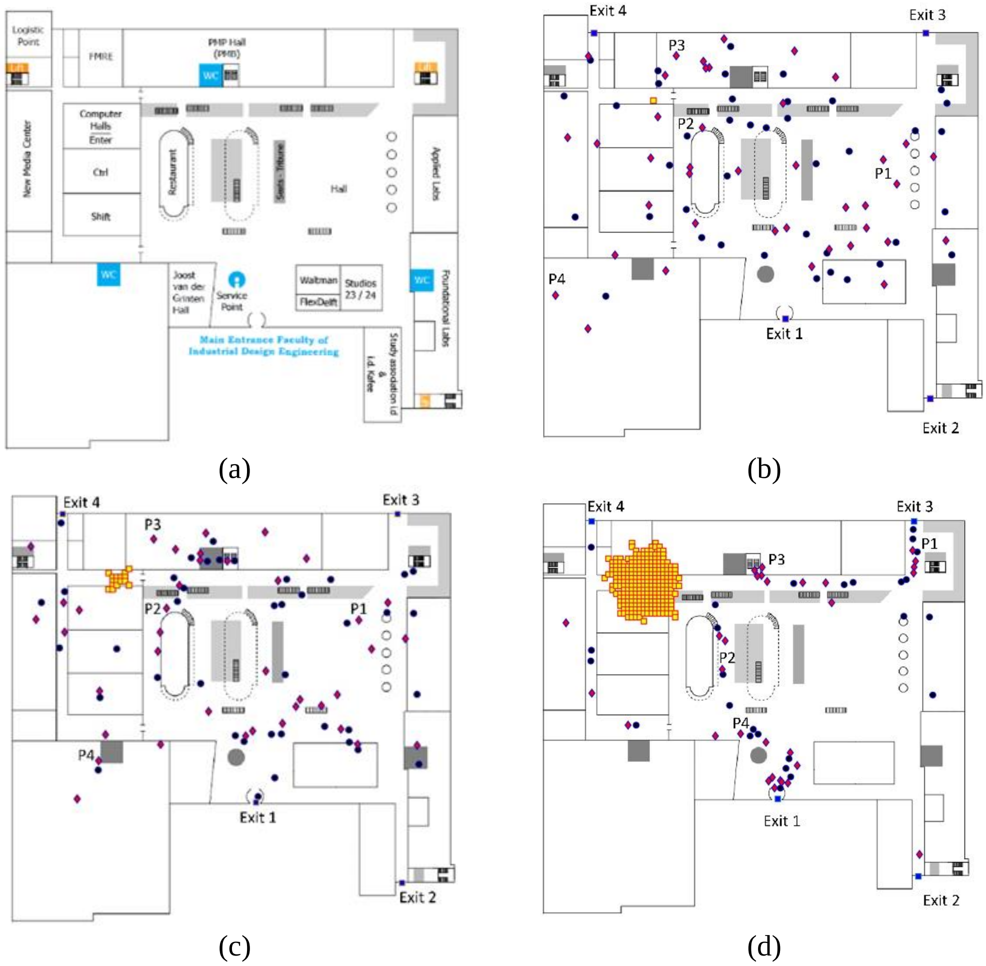

Fig. 6. Simulation of a real-life scenario: (a) The ground floor of Faculty IDE of TU Delft, (b) Initialization of the simulated scenario, (c) Simulated scenario at t = 30s, (d) Simulated scenario at t = 90s.

starting fire (represented by the hollow cube in Fig. 6(b)). The 40 diamonds in the figure represent stakeholders who are able to receive the messages provided by the system, while the circles represent stakeholders who cannot be informed by the system individually. When the fire was detected according to the assumed scenario (t = 20s), it was assumed that the fire alarm worked. The fire proliferated to the neighbor locations with a predefined probability (p = 12.5%). Assumed was that most of the stakeholders started to move towards the nearest exit with constant but randomly generated speeds of motion (a normal distribution with the mean value of 0.75m/s and with a standard deviation of 0.1). However, ten stakeholders neglected the fire alarm and stayed around until the fire front reached them. Every stakeholder was characterized by a collision volume that was considered as an obstruction of the movement of another stakeholder who intended to pass through. This was a basis for the generation of people jams. Based on the basic settings, the simulated situations at t = 30s and t = 90s are shown in Fig. 6(c) and Fig. 6(d), respectively.

4.3 Adaptation of the implemented prototype to the application case

Two types of situations were considered in this scenario, which included (i) fire and (ii) people jams. A people jam was identified when the distances between any two of four or more stakeholders were less than 1 meter. The distance between any two stakeholders was calculated as the length of the shortest path for a stakeholder to follow in the space. The distance between the fire and a stakeholder was considered as the linear distance between the nearest point of the fire front and the location of the stakeholder. The impact coefficient of the fire was set to -1, while the impact coefficient of a people jam was calculated based on the following equation:

$$IC_{\text{people\_jam}} = -0.01 * n^{0.7} \quad (3)$$

where: n is the number of stakeholders in the people jam. To minimize the fluctuations on the calculated SII at a given point in time, a period of time with 11 time points (5 points of data were aggregated from the history and 5 points of data were predicted for the future) was considered in the calculation of the SII of a stakeholder according to the following formula:

$$SII_{s_j} = \sum_{t=1}^{11} w_t * SII_{s_j}(t) \quad (4)$$

where, w_t is the weight for each of the considered points in time, using w_1=w_2=w_{10}=w_{11}=0.025, w_3=w_4=w_8=w_9=0.05, w_5=w_7=0.1, w_6=0.5. The personal danger level was considered as one of two levels according to the value of the calculated SII, namely (i) normal level (SII < 0.1), and (ii) emergent level (SII > 0.1).

The message templates designed for message construction in different conditions are shown in Table 2. For each condition, a message template contains two sentences. The first sentence represents the status of the situation, while the second sentence represents the change of the situation. In addition, when the personal danger level is normal, the informative message includes information about the location of the situation. When the personal danger level is emergent, the informative message includes information about the relationship between the situation and the target stakeholder. In the validation experiment, four stakeholders (marked in Fig. 6) were selected from the varying scenario to see what messages they can receive. The location changes of the stakeholders can be observed. To compare to the proposed MCM, another message construction mechanism was also implemented based on the static context information (SCI) of the concerned stakeholder, which considers the location of the fire only and neglects the proliferation of fire and changes of people jams. The next sub-section will present the simulation results.

4.4 Simulation results

The algorithms have been implemented in the Matlab® developer environment. Using a PC with Intel

Table 2. Predefined message template for informative message construction in different personal situations.

Conditions		Predefined message templates	Examples of informative messages
SII	The situation with the largest impact indicator		
$SII \le 0.1$	Fire	(ds_name, link_v, spa_info). (ds_name, ds_verb, ds_att_adv).	Fire is in the computer room. Fire proliferates slowly.
	People jam	(‘A’, ds_name, ‘(’, ds_att_1,’)’, link_v, spa_info) (ds_att_2, att_verb)	A people jam (10 people) is in front of exit 1. People number is decreasing.
$SII > 0.1$	Fire	(ds_name, link_v, spa_re, ‘you!’). (ds_name, ds_verb, ds_att_adv, ori_re, ‘you’).	Fire is very close to you. Fire proliferates fast away from you.
	People jam	(‘A’, ds_name, ‘(’,ds_att_1,’)’, link_v, spa_re, ‘you!’). (‘The’, ds_name, ds_verb, ds_att_adv, ori_re, ‘you!’).	A people jam (20 people) is in front of you. The people jam moves fast towards you!

Table 3. Personalized messages generated based on the proposed MCM.

No.	Messages generated for the stakeholders	
	At t = 30 s	At t = 90 s
P1	Fire is in the corridor of the C block. Fire proliferates slowly. Please go ahead. The target exit is EXIT 3!	Fire is in the corridor of the C block. Fire proliferates slowly. Please go ahead. The target exit is EXIT 3!
P2	Fire will be close to you! Fire proliferates slowly away from you! Please turn back. The target exit is EXIT 1!	Fire is in the corridor of the C block. Fire proliferates slowly. Please go ahead. The target exit is EXIT 1!
P3	Fire will be close to you! Fire proliferates slowly towards you! Please leave the room. The target exit is EXIT 3!	Fire is in the corridor of the C block. Fire proliferates slowly. Please turn left. The target exit is EXIT 3!
P4	Fire is in the corridor of the C block. Fire proliferates slowly. Please leave the room. The target exit is EXIT 1!	A people jam (12 people) is at the exit ahead. People number is increasing. Please go ahead. The target exit is EXIT 1!

2.50 GHz Core i5 processor and 8 GB RAM, the time needed for message generation for 40 stakeholders was 66 ms. The personalized messages generated for the four concerned stakeholders based on the proposed MCM are shown in Table 3, whereas Table 4 presents the messages generated based on the static context information of the stakeholders. It can be seen from the results that the messages generated based on dynamic context information (DCI) contain not only the information about the current situation, but also trend information related to the change of the situations. In addition, when stakeholders were in emergent situations, e.g. P2 and P3 at t = 30s, the messages generated based on the MCM provided sufficient information for the stakeholders about their personal circumstances. This is important for keeping stakeholders informed with the emergent situation, e.g. close to the fire.

When a stakeholder was in a relatively safe situation, e.g. P4 at t = 90s, the MCM considered the people jam to inform. This is because that the stakeholder was far away from the fire and the implication of the fire on P4 was lower than the people jam formed in front of Exit 1. In addition, information about the changes in the situation was included, e.g. the people number is increasing, which is a piece of additional information and may help the stakeholder to make better judgments. On the other hand, the messages generated based on the static context, contain limited information with regard to the change of the scenario, as shown in Table 4. Although the most critical information was contained in the messages, e.g. where the fire is and what the suggested personal actions are, the messages do not provide sufficient information about the personal context when the fire is not important to the stakeholder, e.g. P4 at t = 90s.

4.5 Human evaluation of messaging

Altogether 18 human subjects (11 males and 7 females) were asked to evaluate the messages

Table 4. Personalized messages generated based on static context information.

No.	Messages generated for the stakeholders	
	At t=30	At t=90
P1	Fire is in the corridor of the C block. Please go ahead. The target exit is EXIT 3!	Fire is in the corridor of the C block. Please go ahead. The target exit is EXIT 3!
P2	Fire is in the corridor of the C block. Please turn back. The target exit is EXIT 1!	Fire is in the corridor of the C block. Please go ahead. The target exit is EXIT 1!
P3	Fire is in the corridor of the C block. Please leave the room. The target exit is EXIT 3!	Fire is in the corridor of the C block. Please turn left. The target exit is EXIT 3!
P4	Fire is in the corridor of the C block. Please leave the room. The target exit is EXIT 1!	Fire is in the corridor of the C block. Please go ahead. The target exit is EXIT 1!

generated based on both approaches. The subjects were master students and Ph. D. students of Harbin Institute of Technology, China. Before the evaluation was taken, the subjects were asked to act as one of the stakeholders in the simulated fire evacuation scenario. The personalized messages generated by both approaches were shown to them during the play of the animation. After these, a focused questionnaire was designed for them to support collecting their opinions, which is shown in Table 5. The questionnaire contained five (informative) statements. For each statement, the subjects were asked to select one of the reflections based on their own judgment, including (i) grade 1: completely disagree, (ii) grade 2: partially disagree, (iii) grade 3: no sense, (iv) grade 4: partially agree, and (v) grade 5: totally agree. Actually, these statements were developed representing five aspects with regard to the quality of the generated message (QoM), which can be seen in Table 5. The results of the human evaluation are shown in Table 6. The evaluation results of each aspect include the mean value and the sample standard deviation (SSD) of the 18 grades given by the subjects.

Table 5. The questionnaire designed for the human evaluation of the generated messages.

Aspects of QoM	Statements	Grades
Usefulness	The messages are necessary for stakeholders to escape from hazardous situations.	(1-5)
Sufficiency	The messages contain sufficient information about the context of the stakeholders.	(1-5)
Informativeness	The information contained in the messages is clear and representative.	(1-5)
Added-value	The messages reduce the anxiety of stakeholders in hazardous situations.	(1-5)
Convincingness	The stakeholders will obey the instructions.	(1-5)

Based on Table 6, it was observed that the mean values provided for the fourth statement (concerning added-value) were the lowest in the case of both approaches. It indicated that providing personalized messages was of limited effectiveness in terms of eliminating the anxiety of stakeholders in the hazardous situation. In addition, the mean values concerning the fifth statement, convincingness, are the highest in both cases. It means that the involved subjects indeed tended to rely on the messages given to them. Most of them wanted to obey the instructions in the hazard-intense situation. Furthermore, with regards to the messages generated by the proposed MCM, the mean values for most of the considered aspects were higher than those generated based on the SCI, except the fourth one. It means that the subjects preferred the messages generated based on the DCI, except when the anxiety of stakeholders was also considered. The reason could be explained as follows. In this case there was more content contained in the messages generated by the MCM than in those generated based on the SCI. It can be understood. Stakeholders in hazardous situations may become much more anxious when they need to read messages with a lot of (technical) information, than when they are provided with concise messages.

In particular, in the answers concerning the fifth aspect, there were two 'Partially agree' option chosen by the subjects for the messages generated by the MCM, while one 'Partially agree', two 'No sense' and one 'Partially disagree' option was chosen for the messages generated based on the SCI. It means that some subjects tended to disregard the messages provided to them, and may disobey the instructions. However, when the implications of the DCI were contained in the messages, the subjects showed a stronger will to obey the received instructions in comparison with

Table 6. Results of the human evaluation of the generated messages.

Aspects of QoM	Messages generated based on DCI		Messages generated based on SCI	
	Mean	SSD	Mean	SSD
Usefulness	4.33	0.84	4.22	0.65
Sufficiency	4.67	0.49	4.06	1.00
Informativeness	4.56	0.51	2.94	1.00
Added-value	3.61	0.85	3.78	1.00
Convincingness	4.89	0.32	4.56	0.92

the situations, when they received messages that contained only SCI information. Messages generated based on SCI probably caused suspicion of the stakeholders with regard to the correctness of the messages. On the other hand, some of the results show large SSDs in the case of the messages generated by SCI, which means that the opinions of the subjects were diverse, whereas their opinions about the messages generated based on the DCI were more consistent. These results indicate that except for usefulness the difference between DCI and SCI based messages is more significant than represented by the difference of the mean value.

5. Discussion, conclusions, and future research

5.1. Discussion of the major findings

By using informing CPSs, the hazard in critical events and situations can be reduced. An opportunity for this is providing context-dependent informative or instructive messages for stakeholders who are involved. As demonstrated in the state of the art in the field of automated and context-sensitive messaging, dynamically changing situations of stakeholders should be dealt with in order to increase the quality of informing. However, the existing solutions only consider static context information of stakeholders and they can hardly be applied to process the heterogeneous, unstructured and dynamic context of stakeholders. Towards this, the proposed personalized message construction depends on a real-time assessment of the implications of the situations that are relevant to stakeholders. In this way, the most relevant situation can be selected and the content of messages can be determined based on the descriptive information of the selected situation. Another important consideration is that the proposed MCM is able to calculate the personal danger level of individual stakeholders. This enables the MCM to choose a proper template for message construction. The functionalities specified for the MCM are consistent with the technical requirements.

The proposed MCM was implemented and tested in a simulated real-life scenario: an indoor fire evacuation guiding application. Based on the applied template-based approach, personalized messages can be generated in a real-time manner. The generated messages adaptively represent the personal context of the (assumable) stakeholders. To test the quality of the generated messages (QoM), opinions from human evaluators were collected with regard to the usefulness, sufficiency, informativeness, added-value and convincingness of the generated messages. Despite the sampling size of the concerned human evaluators was limited, valuable findings were obtained. On the one hand, most of the involved stakeholders believed that the proposed MCM provides more useful, sufficient, informative and convincing information about personal context and expected actions than the messages constructed based on static context information only. On the other hand, when dynamic context information is contained in the personalized messages, the involved stakeholders showed a higher level of agreement on the results of the QoM.

The results of validation imply that the quality of information contained in personalized messages could help stakeholders to make better judgments, at the same time, the obedience of the stakeholders to the given instructions could be stimulated. On the other hand, as demonstrated by the results of human evaluation, stakeholders might disobey the instructions given to them in the considered application case, or in particular, in hazardous situations. It implies that if any disobedience situation happens and observed, it does not make sense for the I-CPSs to provide any follow-up messages. The disobedience of stakeholders should be considered as a part of the dynamic context of the stakeholders and handled by the I-CPSs. This is recognized as the limitation of the proposed work.

5.2. Conclusions

With the objective to inform stakeholders about their dynamically changing individual contexts, this paper proposes a personalized messages construction mechanism. Based on the conducted research, the following conclusions have been drawn.

(i) The proposed strategy for dynamic context assessment enables quantitative evaluation of the relevance of situations to individual stakeholders, which can be considered as a basis for determining the content of messages utilized to inform the stakeholders.

(ii) The proposed template-based message construction mechanism proved to be an effective approach to generating both informative and instructive messages according to the dynamically changing context of stakeholders in a real-time manner.

(iii) In the presented case study, messages generated based on dynamic context information enabled the stakeholders (e.g. escapees in a burning building) to have better awareness of the situation in comparison with the messages generated based on static context information.

(iv) The proposed message construction mechanism provided more relevant information to stakeholders in the investigated hazard-intense application and enabled better decision making concerning the execution of the personalized action plans.

(v) According to the results of the human evaluation, the messages generated by the proposed MCM were considered more useful, sufficient, informative and convincing than the messages generated based on static context information only.

5.3. Future research

In the conducted research, the impact coefficients of different situations on stakeholders were predefined, such as by using Eq. (3). However, in real-life applications, the implication of situations on entities should be estimated and learned in real-time based on a synergic processing of the actual changes of situations and the consequences caused by the changes. In addition, due to the fact that stakeholders may disobey the instructions given to them, the messaging system should be aware of the tendency of disobeying of concerned stakeholders and generate adaption strategies. These specific issues are in the focus of our follow-up research. Longer term research may consider the following investigation and/or developments: (i) integration of the dynamic context computation-based messaging mechanisms with context-dependent system-level problem solving mechanisms, (ii) implementation of the combined mechanisms in an application independent platform, (iii) developing developer and system interfaces for the combined reasoning platform, and (iv) embedding the combined reasoning platform in various informing cyber-physical systems and validating it in several different application cases.

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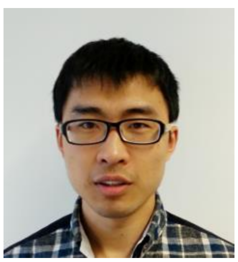

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