A Component Model for Managing Covid-19 Crisis

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Summary
Covid-19 posed a serious threat to public health worldwide, especially in the absence of vaccines or medicines. The only viable strategies to combat a virus with a high infection rate were to apply lock-down strategies, transport ban, social and physical distancing. In this work, we provide a domain-specific component model for crisis management. The model allows for building a plan for managing Covid-19 crisis and use the plan as a template to generate a system specific for managing that crisis. The crisis component model is derived from X-MAN II, a generic component model that we have developed for the aircraft industry
Key words:
X-MAN II; Covid-19; Crisis Management; Component model; Crisis component model, Domain-specific component model; Lock-down; Physical distancing.

1. Introduction

The outbreak of a novel strain of Corona virus, known as Covid-19 or 2019-nCov, posed a serious threat to public health worldwide [1]. The first confirmed case of the virus dates to December 2019 in Wuhan, China. Since then, the World Health Organization (WHO) has confirmed 180 million infections with a death toll over 4 million. Covid-19 is characterized by its rapid spread pattern which is further maximized due to globalization and urbanization. The current case fatality1 of confirmed Covid-19 cases ranges from 0.1% (in Singapore) to 19.7% (in Yemen) which on the average exceeds that of SARS (at 3.4%) [1] but still less than MERS (at 14.36%). The scale of Covid-19's impact and the burden it places on health systems have led WHO to declare it as a global pandemic [2].

Considering the wide spread of infections, policymakers devoted every effort and resource to alleviate the impact of Covid-19 on various walks of daily life, by applying several policies. The first of these, mainly led by advanced counties, targets the development of vaccines. These efforts have resulted in many vaccines with various levels of effectiveness and side effects [3], [4]. But the availability and reachability to any of these vaccines is still a difficulty for many counties [5]. Trial results have shown that many of these vaccines decrease the risk of infection after 12 days [6]. The second policy is to rely on the development of heard immunity [7], [8]. Herd immunity can be developed by allowing infection to spread in the population until a sufficient size of the population is infected and developed self-immunity against the virus. Unfortunately, not only this measure overburdens health services in even the most advanced economies, but it also results in many additional deaths. The third policy relies on lock-down, physical, and social distancing measures to restrict residents' mobility. Published statistics on the effect of this policy has revealed its effectiveness in reducing the spread of infection [9], [10].

However, although lock-down strategies are effective in containing and limiting the spread of the virus, they pose a drastic impact on the economy activity due to mobility restriction [11]. Economies worldwide has witnessed a deep downturn in even the largest economies leaving a huge dent in global economy. Losses incurred by lock-down policies have been reported in billions with informal labor and daily workers among the first to feel the impact, leading in some cases to civil unrest [12].

In this work, we study and analyze the crisis management domain to specify a component model dedicated to designing and deploying (executing) plans for managing a crisis. This kind of model is a domain-specific component model [13]. It enables crisis centers build plans and generate systems that can be used to manage a crisis within one or more geographical regions. The model defines lock-down regions with borders that change dynamically in response to real-time feed of infection data, a hierarchical organizational structure of command-and-control units (crisis management units), and a flow modelling resident mobility and supply chains. Our focus and contribution in this work is a component model for the domain of crisis management. Our model is aligned with the endeavor towards a sustainable smart city and society against Covid-19 pandemic. But it still can be used to handle many other kinds of crises, natural or artificial.

The sequel of this paper is organized as follows. We establish a context for this work in terms of a survey of related literature (Section 2), then present a general analysis of the crisis management domain (Section 3), argue why XMAN II component model is a suitable basis for building a domain-specific component model for crises management (Section 4), and build our new model in Section 5. Then we demonstrate by a simple example how the component

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model can be used to design a plan for combating Covid-19 infection (Section 6). We discuss our results (in Section 7) and conclude with our results in Section 8.

2. Context of our Work

The first Covid-19 confirmed cases have motivated researchers to investigate the medical characteristics of the virus [14], detection methods [15], infection prevention measures [16] and developing new vaccines and medicines [17]. Research efforts have also exploited technologies to allay the pandemic adverse impacts on daily life of societies worldwide. Our focus in this section is to survey software technologies designed to assist in managing crises and mitigating their impacts on societies, with emphasis on evolving technologies to contain the spread of Covid-19 infection. We are not interested in mobile applications or IoT devices as these are just small building blocks in larger frameworks. Our focus is on software models or patterns used in the design of systems to manages a pandemic crisis.

A number of software models have been incorporated into systems and frameworks to mitigate the adverse impacts of natural, industrial, and pandemic disasters. Before the outbreak of Covid-19, existing models have focused on rescue and firefighting [18] and telemedicine [19]. There is however a wealth of mathematical and machine learning models implemented to predict, control or diagnose Covid-19 infections. We are only interested in one of these which exploits control theory in controlling the infection R_0 [20], [21].

G. Stewart *et al*. developed a tool that modelled Covid-19 pandemic as an unstable, open-loop engineering system [20]. This kind of system grows exponentially if its behavior has been not altered in some way, and to stabilize and control its behavior, control theory provides a feedback mechanism [21]. The tool applies non-pharmaceutical intervention measures (NPIs) to control the infection rate (R0); where R_0 is a measure of the number of persons who contracted the disease from an already infected person [22]. NPI measures focused on slowing and suppressing the disease.

B. Traore et al. used software services (a kind of component model) to support remote crisis management [19]. The services expose functions for the identification, analysis and forecasting a crisis; and additional functions that generates directions to help organizations suppress or cope with impacts of a crisis. The approach is the first to integrate telemedicine, transportation, and heath organizations to save more lives. The system has been simulated using data collected on a tsunami that hit Cannes (France) on the 21st of May 2003.

K. Domdouzis et al. focused on service-oriented architecture (SOA) to develop ATHENA Crisis Management Distributed System [18]. The system used data published on social media to evaluate the severity of a crisis and the appropriate actions to be coordinated in response to a crisis. The system customized the SOA architecture pattern to suit crisis management and illustrated its usefulness to stakeholders with different technical levels.

J. Kienzle et al. defined a reference case study focused on a crisis management system (CMS) and dedicated for aspect-oriented modelling (AOM) research community [23]. The value of this work lies in the information it provides on the domain of crisis management, though not complete, but sufficient for the goals of our work.

These systems and tools have exploited the power of mathematical theory, software architecture, and programming paradigms to build infrastructures for crisis identification, analysis, and management. Our approach on the other hand, is a component model for the crisis management domain defined by propagating domain constraints into the generic component model X-MAN II. Before outlining X-MAN II, we present in the next section a set of relevant properties required in the domain of crisis management, to use as domain constraints in defining the new component model. We will give the name crisis component model to our new model.

3. The Crisis Management Domain

In this section we analyze the domain of crisis management and identify its basic characteristics. Our analysis is based on a case study presented in [23].

The domain requires several properties and provided services. It provides data collection services by means of local or remote sensors, field workers, and members of the community. The data is used in analyzing a potential crisis situation, and if a crisis has been identified, its severity is assessed and factors escalating the crisis are quantified. Based on results of the analysis, a crisis management plan to mitigate adverse impacts of the crisis is set, usually by crisis management centers. A crisis plan may involve a few actions to counter a crisis of a given type. In the case of industrial crises such as radioactive or chemical leak, actions may involve combating causes of the crisis, in tandem with efforts to evacuate those in risk. In other crisis situations, plans may involve lock-down measures, travel bans, physical and social distancing. The later policies were the only viable strategy to manage the infection rate (R0) of Covid-19 within a controllable range. Similar policies are applied for other kinds of crises such as severe weather conditions. For example, weather conditions may force a lock-down policy to protect communities from life threatening dangers such as debris carried by strong winds, snowstorms, heavy rain causing floods, etc. [24], [25].

All crisis management plans involve dispatching specialized teams to deal with adverse impacts of a crisis; provision of rescue and medical services; or handling causes of crises. Archiving data about a crisis or data generated during crisis management efforts is vital for future reuse in similar situation. Therefore, it is a core service in the domain to collect, analyze and archive crises data and reuse it in future analysis [26].

The domain of crisis management is characterized by a rich behavior of communicating commands among parties participating in handling a crisis, as well as orchestrating operations of those parties. Commands may change to cope with the dynamic behavior of crises. For example, Covid-19 infection changes as a result of social, business and travel activities. Therefore, continuous data feed on the spread of infection may lead to new updates on commands, instructions, or directives. These updates need to be communicated to organizations responsible of their implementation. Therefore, and regardless of the kind of the crisis, making policies and communicating them to implementation parties and orchestrating these parties' operations is a shared behavior [27].

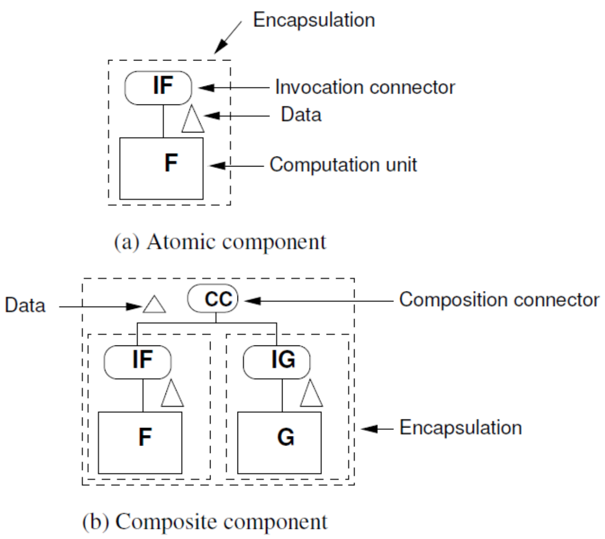

Fig. 1 Encapsulation and compositionality in components.

Supply chains are also a major economic activity that are likely to be affected by a large-scale crisis. In Covid-19 times, businesses must create contingency plans to deal with different demand environments, diversify their supply base to mitigate supply shock; manage panic buying situations, and invest in making supply chain workers safer. These plans are critical for maintaining a sustainable supply chain during Covid-19 pandemic, locally and internationally [28]. In this work, we are interested in local supply chains, but our argument can be generalized to global supply chains. In particular, we are interested in inventory depletion as a result of consumers stocking up in response to potential lock-down policies. Furthermore, delivery options are of major concern in the domain of crisis management as they become more appealing to consumers and retailers in crisis times. Therefore, the main goal would be to schedule the transfer of supplies on specific routes without endangering the producers' workers, the supply chain workers, or the consumers [29], [30].

To this end, we conclude our analysis of the domain with a summary of its main intrinsic properties. These include data storage, analysis, and archiving; identification of factors escalating adverse impacts of a crisis, ways to mitigate crises effects on human lives, businesses and natural assets; communicating commands and directives amongst involved parties; managing communities and their activities; potential lock-down policies, travel bans, social and physical distancing; and maintaining a sustainable supply chain.

In the next section, we present a generic component model (X-MAN II) to use as a basis for defining a crisis component model (CCM). We argue that X-MAN II characteristics make it a viable model for our goals in this work.

4. X-MAN II Component Model

X-MAN II has two types of basic elements: (i) computation units, and (ii) connectors. A computation unit U is a software module which encapsulates computation. We mean by encapsulation that U's methods do not call external methods; rather, when invoked, all their computation occurs in U. Thus, U could be thought of as a class that does not call methods in other classes.

There are two types of connectors: (i) invocation, and (ii) composition. An invocation connector is connected to a computation unit U so as to provide a standardized means of access to the methods of U.

A composition connector encapsulates control. It is used to define and orchestrate the control for a set of components (atomic or composite). For example, a sequencer connector that composes the components C1, . . ., Cn can call methods in C1, . . ., Cn in that order. Another example is a selector connector, which selects (according to some specified condition) one of the components it composes and calls its methods.

Components are defined using computation units and connectors. There are two types of components: (i) atomic, and (ii) composite (see Fig. 1). An atomic component consists of a computation unit and an invocation connector that exposes an interface to the component. A composite component consists of a set of components (atomic or composite) composed by a composition connector. The composition connector exposes an interface to the composite.

A component in X-MAN II (atomic or composite) allows the definition of placeholders for its own data at design time [31]. These placeholders are indicated by triangles in Fig. 1. Henceforth, an atomic component encapsulates computation and data; and a composite component encapsulates data, computation, and control.

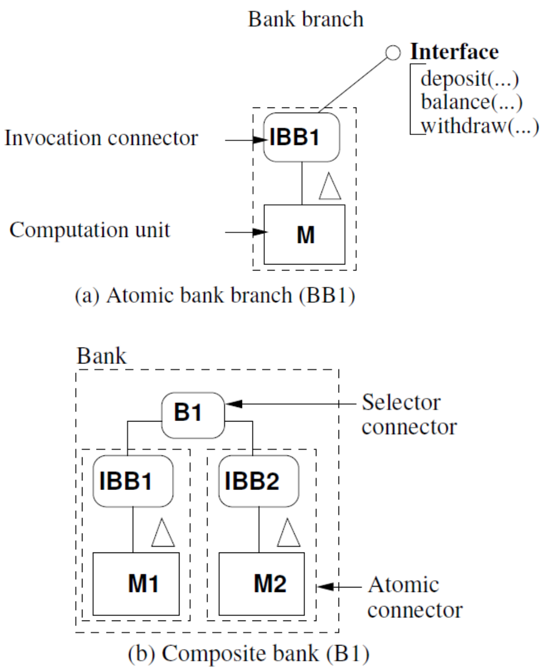

Fig. 2 Sample atomic and composite components in a bank example.

To demonstrate design with X-MAN II, consider a software module which provides bank branch services: deposit, withdraw, and balance. An atomic component for a bank branch BB11 may be defined with an invocation connector IBB1 and the software module M (Fig. 2a). The composite component, a bank B1, may be defined as a composition of the atomic components BB11 and BB12 using a selector connector (Fig. 2b). A bank network composite component may also be composed (from banks) using a selector connector, since the network has to choose the bank with the branch to which the customer's account belongs. In X-MAN II, invocation and composition connectors form a hierarchy. This means that composition is done in a hierarchical manner. Furthermore, each composition preserves encapsulation. This kind of compositionality is the distinguishing feature of the component model. An atomic component encapsulates computation and data (Fig. 1a), namely the computation encapsulated by its computation unit and data placeholders. A composite component encapsulates data, computation, and control (Fig. 1b). The computation it encapsulates is that encapsulated in its subcomponents; the control it encapsulates is that encapsulated by its composition connector; and the data placeholders it encapsulates for the composite. In a composite, the encapsulation in the sub-components is preserved. Indeed, the hierarchical nature of the connectors means that composite components are self-similar to their sub-components; this property provides a basis for hierarchical composition.

Encapsulation; hierarchical composition; and flow of control and data form a set of properties highly required in the crisis management domain. Insulation, quarantine, and lock-down strategies, mainly applied in pandemic times, are different forms of encapsulation. Whereas hierarchical composition is a representation of an organizational structure of authorities managing a crisis. Moreover, flow of control and data can be used to express supply chains, mobility of commuters or communication of instructions. In the next section, we study and investigate how to employ X-MAN II properties to accommodate domain constraints of crisis management [13].

5. A Component Model for the Crisis Management Domain

We can derive a component model specific to a given domain by propagating domain constraints into a generic component model [13], [32]. A generic component model however, should provide elements to accommodate core properties required in the domain. For example, the best component model for a domain characterized by dominant control behavior is a component model that has explicit control elements. Otherwise, control behavior needs to be augmented manually into elements of the component model, which may not be the most efficient solution. 5.1. Components

5.1 Components

We start by identifying specific components required in the domain. Based on our analysis in the previous section, the domain requires data storage, processing, and archiving services. Henceforth, we need a software module (a class or a library of classes) which provides data operations such as add, update, and delete. The module encapsulates the necessary computation and has access to data store (a file or a database) to perform data operations.

The processing requirements in the domain is performed using algorithms that depend on the crisis type. For example, algorithms used in analyzing the infection behavior of Covid-19 [33] are different from those needed to analyze the potential trajectory of a hurricane [34], [35]. These algorithms are used to identify factors causing a crisis to escalate and they are subject to performance enhancements and scope improvements. As such, encapsulation of these algorithm in an atomic component is a tactic usually applied to improve the modifiability quality attribute [36].

Furthermore, the domain requires additional functions for gathering information on subjects to be protected from the adverse impacts of a crisis. These subjects can be humans, assets of economic value or critical natural resources. Usually, the required information encompasses data on affected subjects, their needs (food, water, fuel, medical supplies and medical support, etc.), commands and directions to communicate to subjects in order to minimize impacts of a crisis, products and waste.

In crisis times, it is also important to manage stock against panic buying situations through a stock management module (inventory). This module provides services to monitor current stock, re-stocking, and orders, etc.

Accordingly, we define atomic components from the software modules outlined above. The first atomic component, a datastore, is created from a module that provides data access operations on a file or a database. The second atomic component, a dataAnalytics, is created from a module that provides a set of algorithms to analyze a situation and assess a potential crisis. The third is an atomic component, protectionZone, that partitions the subjects into zones of protection. The fourth is an inventory atomic component, inventory, to enable crisis centers manage vital stock. Fig. 3 show types of atomic components in the component model.

Let us demonstrate these components by an example from the domain of Covid-19 crisis management. A datastore component holds data on infection and geographic locations; fatalities; hospitals; medical teams; medical supplies and equipment. We are not considering here data modelling as the component performs its services against a file or a database. The dataAnalytics component provides algorithms for calculating R_0 (the infection rate) and data visualization [37], [38], [39]. The protectionZone component can be a building, a geographic area from an urban or rural region identified using GIS parameters. The invocation connector rule in these components can either be played by a machine (server) or a human representative. Therefore, we will use the term representative instead of the ”invocation connector”.

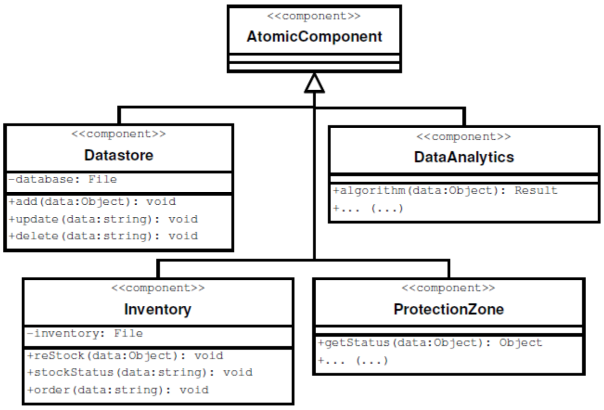

Fig. 3 Structure of atomic components.

5.2 Connectors

We have already used the invocation connector in constructing atomic components. This connector is renamed with an expressive name (representative) to hint its role in the specific component model. In Section 3, we have argued that command and control is a core requirement of the crisis management domain. In this section, we present the different patterns of control behavior in the domain and give each one of these an expressive name from the domain.

The simplest control patterns performed by distributed, crisis management units are either selection, piping, or sequencing. There is of course iteration which is not considered here as we are interested in designing plans [40], not deploying them. The selection pattern in the domain is required when a crisis management unit needs to decide where to deliver information or supplies. Let’s consider two protectionZones A and B and a crisis management unit CMU1 responsible for controlling the flows of command and supplies to these two zones. Based on provided directions (constraints), CMU1 will route the flow to either A or B. In Fig. 4a, the flow of control or supplies is coordinated by CMU1 to A. The representative IA delivers supplies and invokes the necessary services on A, then returns a result (if any) and makes it accessible to CMU1.

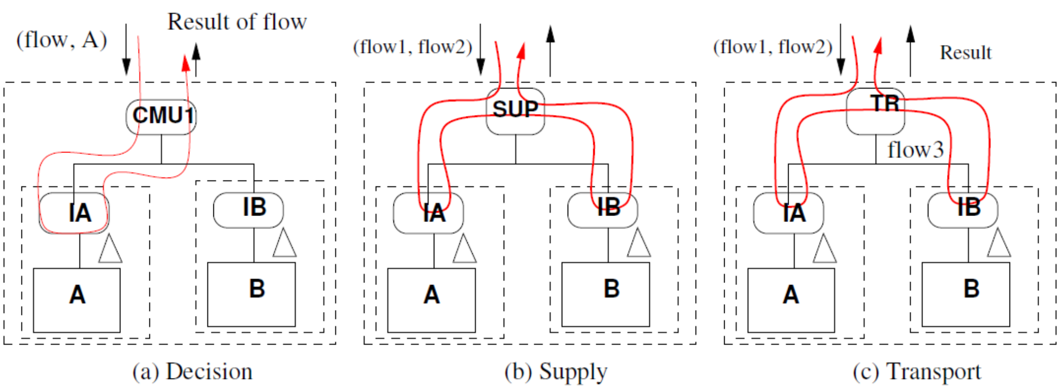

Fig. 4 Elementary control patterns of connectors.

We call the crisis management unit performing this behavior pattern a decision.

In other situations, a crisis management unit need to route command or supplies in a prescribed order, without needing replies from connected zones. This behavior is an elementary supply chain activity. X-MAN II provides the sequensor connector for this pattern of control. In the context of this domain, this connector is a crisis management unit performing supply chain responsibilities. We call this kind of unit the supply. Fig. 4b shows a supply unit passing flow1 and flow2 to A and B.

A third control behavior is manifested when a flow is routed to a number of ordered components (zones) such that when a component receives a flow, it generates an output, which in turn, is piped into next component and so forth. The last component in the sequence may produce a result. This behavior is similar to a UNIX pipe. In our domain, a dedicated crisis management unit performs this control pattern. We call this unit a transport unit. Fig. 4c shows two components (zones) connected by a transport unit TR. The unit TR routes flow1 to A, where A generates as a result flow3. TR routes the pair (flow2; flow3) to B and B makes and resulting flows accessible to TR.

In Fig. 4, the crisis management units act as a composition connectors. They compose atomic protectionZones to create composite protectionZones. In a composite, computation is encapsulated in atomic protectionZones and control is encapsulated in decision, sequensor, and transport crisis management units.

In the next section, we present an example to demonstrate a lock-down plan to combat the spread of Covid-19 infection in two regions in a city.

6. Example Covid-19 Plan

Consider two buildings with Covid-19 infections. Let's assume that a crisis center preferred a lock-down strategy to combat the infection. Dwellers of the two buildings are not allowed to exchange any kind of physical objects. The crisis center created a datastore to store, analyze and archive infection data. Furthermore, the center has contracted with a chain store to deliver supplies for the two buildings' dwellers. Let's use our crisis component model to design a plan for managing this miniature crisis.

We can create two protection-zone components, one for each building (B1 and B2). Each protection zone is assigned a representative (R1 and R2) to perform any tasks required by a crisis center. In each zone, dwellers can only respond to their representative requests. Based on the requirements above, the two protection zones should not exchange any physical objects; and maintain physical and social distancing. Accordingly, the two zones can be composed in one composite using a supply SUP crisis management unit. The responsibility of SUP is to disseminate and collect information or deliver supplies to B1 and B2. We call the composite B12.

In the requirements, a data store is needed to store data on infection, delivered supplies and any other relevant data. Therefore, a protection zone of type datastore is needed; let's give it the name AR. This zone is best composed with BAR using a crisis unit of type decision.

Finally, we add a protection zone of type stock and give it the name ST. Then, we compose ST with BAR using a crisis management unit of type decision which coordinate between the ST and the BAR zones. The new composite is given the name SBAR.
The final design of a plan (SBAR) to manage this crisis provides a number of services (See Fig. 5):

- Collecting needs of B1 and B2 through the path (ISBAR, IBAR, SUB, IB1, SUB, IB2).
- Order supplies from the store through the path (ISBAR, ST).
- Deliver supplies to BAR through the path (ISBAR, IBAR, SUB, IB1, SUB, IB2).
- Archive information on delivered supplies through the path (ISBAR, IBAR, AR).

Other services are possible depending on the services provided by the modules of the atomic protection zones. The paths themselves are decided by the constraints passed to SBAR and BAR zones.

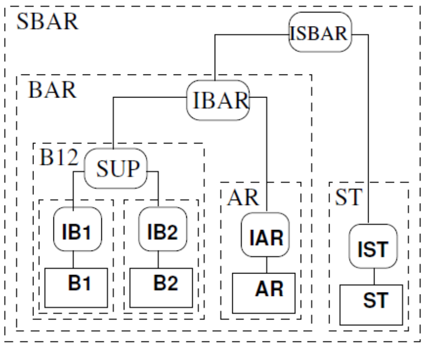

Fig. 5 An example plan designed for Covid-19.

7. Analysis and Comparison

We have presented a new crisis component model defined by propagating domain constraints into components and connectors of X-MAN II. Using the set of pre-defined atomic components and composition connectors, we can build plans to disaster situations. In these plans, atomic components play specific roles including those to be protected and connectors play the role of crisis units. The semantics of the composition scheme of X-MAN II is used to compose larger protection zones from sub-zones, encapsulating larger areas to protect while adding resources (stores of supplies and data). The model can be used to structure as large as necessary to manage the adverse impacts of a crisis. Managing a crisis with a component model defined for this domain is a novel approach. Especially, as the model defines pre-defined compositional control templates and a means to create as many as required of protection zones.

Existing approaches manage crisis situations by deploying and using specialized information system. In [18], authors propose to design a software system using a service-oriented architecture (SOA) pattern. The system is generic with respect to crisis management and fixed. Other systems used services to create a distributed crisis managements tools [19] or just implemented a mathematical model as in [20]. While the former system is similar to [18], the later handles a specific kind of crisis, namely controlling Covid-19 infections through R_0. Furthermore, there exists many models utilizing data analytics methods to predict the spread of Covid-19 infections and diagnosis of potential cases of infection. These models are quite many and no different from [20].

Compared to these approaches, we presented in this work a component-based approach for managing a crisis. The model allows for construction a crisis management plan and gives the opportunity to compile a system dedicated for managing that specific crisis. Our claim relies on a decade of experience using X-MAN II the aircraft industry.

8. Conclusion

In this work, we have contributed a crisis component model (CCN). The model allows creating crisis management plans using pre-defined control units representing crisis management teams and protection zones representing communities and businesses. We have defined CCN by propagating domain constraints into X-MAN II's templates of components and connectors. CCN has been applied to simple crisis to build a crisis management plan which serves as a template to deploy a software system dedicated to managing that crisis.

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