MANAGEMENT OF UNEXPECTED EVENTS IN EMERGENCY SCENARIOS

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To my family

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EXECUTIVE SUMMARY

Emergency management in buildings and infrastructures represents an always-pressing issue in each phase of building lifecycle.

The traditional approach to the emergency management is based on a deterministic prevision of the main scenarios, regardless of contextual, changing and unexpected events that may happen and seriously affect the effectiveness of emergency measures. The current approach results affected by several weaknesses due to a poor and inefficient data acquisition regarding the evolving scenario and to the bottlenecks in the decision flow, deriving from a too rigid hierarchical workflow.

This work has been developed with the purpose to propose a novel approach in the emergency management, aiming at overcoming the limits of the actual approach. The contribution of this dissertation lies on the development of a new methodology in the emergency management based on the principles of real-time effectiveness, resilience and unconventional problem solving. A shift from a deterministic to a contingent approach is proposed, leveraging the system's flexibility and adaptability to changing scenarios, founded on the application of the Holonic Theory to the emergency management. This theory promotes a higher autonomy and cooperation among the actors of the lowest level of the hierarchy, as a response to a too rigid hierarchical workflow, often affected by bottlenecks in the decision flow that may result fatal in critical scenarios like the emergency ones.

The research has conducted to the definition of a system architecture as support to the standard rescue operations, which improves the usual approach supplying more updated and significant information from different sources and investigating unusual solutions for rescue purposes in case of unforeseen events. In order to concretize the developed architectural principle, the methodology has been applied to a case study, by creating a specific system architecture. It relies on the means of BIM (Building Information Modelling), as comprehensive building information provider, Bayesian Networks to make the decision flow more flexible and able to cope with uncertainties and Virtual Reality engines to collect data from heterogeneous sources and test the overall system. The bottlenecks in the process flow result considerably reduced, providing the system with a faster capability to face unexpected events, endowing it with the required resilience and adaptability. The dissertation concludes by outlining the main contributions of the research carried out and recommending interesting research topics for future development.

ITALIAN VERSION

La gestione delle emergenze negli edifici rappresenta un tema sensibile in ogni fase del ciclo di vita delle strutture. Il tradizionale approccio alla gestione delle emergenze si basa sulla previsione deterministica dei principali scenari che potrebbero verificarsi, non tenendo conto degli eventi casuali e inaspettati che potrebbero verificarsi influendo negativamente sulle operazioni da eseguire in caso di emergenza. L'approccio attuale presenta diversi punti di debolezza dovuti ad un'acquisizione di dati sullo stato di emergenza scarsa e poco efficiente e a diversi "colli di bottiglia" nel processo decisionale, che appare irrigidito dal suo carattere eccessivamente gerarchico.

Questo lavoro nasce dall'idea di proporre un approccio innovativo alla gestione delle emergenze, che sia di supporto a quello attuale, portandolo a superarne i limiti riscontrati. Il contributo scientifico di questa tesi, consiste nello sviluppo di una metodologia nella gestione delle emergenze che presenta innovative caratteristiche di efficienza in tempo reale, resilienza e capacità di risoluzione di problemi in modi non convenzionali. Si propone dunque un cambio di rotta da un approccio deterministico ad uno volto ad affrontare la contingenza delle situazioni che potrebbero verificarsi, elevando la flessibilità e adattabilità del sistema, attraverso l'applicazione della teoria "olonica", la quale promuove maggiore autonomia e cooperazione tra i livelli più bassi della gerarchia in risposta a un workflow troppo rigido, che può generare impedimenti che in casi critici come quelli delle emergenze, possono risultare fatali.

La ricerca ha condotto alla definizione di un'architettura di sistema a supporto delle operazioni standard previste da normativa, rendendole più efficienti attraverso l'utilizzo di dati aggiornati ed eterogenei, proponendo soluzioni alternative in caso di imprevisti, rapidamente calcolate. La metodologia è stata implementata in un caso studio, dettagliandone l'architettura di sistema fondata sull'utilizzo di modelli BIM come "contenitori" di informazioni aggiornate, coerenti e complete sull'edificio, di Reti Bayesiane per selezionare le azioni alternative più promettenti analizzando rapidamente le serie di dati al momento disponibili e una piattaforma di Realtà Virtuale come collettore di dati provenienti da fonti eterogenee e ambiente di simulazione con elementi di Intelligenza Artificiale. I risultati che dimostrano l'alta resilienza e reattività del sistema e spunti per possibili sviluppi futuri di ricerca scientifica concludono il lavoro di tesi.

CHAPTER 1

Introduction to the thesis

1. INTRODUCTION

Safety management is a widely and always pressing matter of studies and scientific research. Several branches of specializations have been raised to supply a response to the criticalities linked to this subject. The overall objective is to improve safety of people in built environment in case of natural or human caused disasters, involving several phases, starting from a foresighted design of buildings and infrastructures to the elaboration of emergency plans according to specific norms.

Several methods have been applied to assess the emergency management: beginning from the deep study of the causing phenomena (e.g. with the FSE – Fire Safety Engineering, flood management) through several approaches to foresee the systems' evolution and simulate escaping routes in emergencies scenarios. Alongside studies of physical evolution of the systems, behavioural and psychological aspects involved in the emergencies scenarios have been deeply analysed in order to improve rescue operations.

Recently, simulation tools have been increased and fine-tuned to support these studies in a time and cost effective manner, enabling always more sophisticated analysis of the scenarios during emergencies events. Moreover, the computerised representation of the investigated environment is widely spreading since it enables to explore cheaply and deeply the buildings and infrastructures' vulnerabilities since the early design stages.

Nevertheless, the study of some aspects that have a great influence on the emergency management operations, like the acquisition of data during the emergency and the management of unexpected events that may occur in continuously evolving scenarios, have not yet reached a mature level. Therefore, finding these aspects greatly interesting in the research perspective, this work has focused on them, in order to develop a methodology in response of the relative criticalities.

This dissertation starts from the analysis of the limits of the actual emergency management, which can be can be shortlisted as follows:

- **Not effective information flow**: static information resources, like emergency plans hang on walls; do not reflect the real evolvement of the emergency, supplying only static and rigid information about escaping from a place during a "conventional" emergency situation. Moreover, they are not always intuitive or easily accessible for evacuees.

- **Fixed scenario-based:** unexpected events have a great impact during the rescue operations and can seriously affect them. Unforeseen events in many cases have caused the failure of rescue activities; nevertheless, their possible occurring continues to be not sufficiently taken into account in the current approach.

- **Not flexible workflow**: actual emergency plans and operations are based on a hierarchical approach which is not enough flexible and adaptive to cope with changing and unexpected situation. Decisions are always demanded to the higher level in the hierarchical management organization, creating bottlenecks in the decision flow that involve a delay in the operations executions that may become fatal.

Examples of complications in the emergency operations due to the aforementioned aspects may be found in some of the most recent and serious events occurred:

1) During the emergency response to the September 11, 2001 attack on the World Trade Centre, emergency response commanders on the scene were unable to communicate to '911' Public Service Access Points (PSAP) that people should evacuate the building. As a result, PSAP operators complied with New York City's standard operating procedure for hi-rise fires and advised callers to stay in impacted buildings [1]. The '911' system was inadequate for handling a major disaster and could not adapt to the emergency. The final death toll 2.749 may have been substantially reduced if the PSAP's were adaptive in coping with the overload. Commanders trying to evacuate fire fighters from the north tower during the World Trade Centre disaster were seriously hampered by ineffective radio communications; the final death toll 343 of New York fire fighters may also have been substantially reduced if the system controlling the radio communications was also adaptive. [1]
2) The Grenfell Tower fire produced a high number of victims not only for technical reasons due to the employment of a not proper cladding system and to a lack of separated fire boxes into the building but also to a mistake in the emergency evaluation.

The “stay put” strategy led by a tardive declaration of the situation as a major incident with the consequent delay of one hour in the evacuation process has revealed as a fatal mistake in the rescue operations. [2]

3) The fire in the Rhode Island station club represents instead an example of how a not profound knowledge of the building in which people were located affected the evacuation process: a study has demonstrated that people did not use alternative ways out since they ignored their presence.

   While the main exit doors were obstructed by the smoke presence, there were no indication to use alternative paths to escape from the building; therefore, the evacuation process was affected by a fatal delay. [3]

The tragic evolution of these events supports our motivation in the search of possible improvements in the actual emergency management approach.

1.1. Aim

This dissertation has been conceived to assess a novel approach to face emergency management in case of unexpected events. The foundation of the method is to integrate general data and provide fast and effective ways to react to emergencies in case of unexpected events by supplying solutions to face unforeseen situations that are not covered by a traditional deterministic approach. A shift in the emergency management is proposed to overcome the limits of a knowledge-based approach, which claims to provide all the possible scenarios that may occur without taking into account possible accidental events that instead usually affect the rescue operations.

In order to provide a methodology able to tackle the observed weaknesses, we have developed a novel approach based on the shortlisted architectural principles:

1) **Real-time effectiveness:** the system must react dynamically to an always-changing situation occurring during emergency scenarios. This condition implies the consideration of “real-time” as a reactive time sufficient to face the changed situation;
2) **Resilience**: the system must be adaptive to incidental changes. More specifically, emergencies operations have to be guaranteed also in case of obstructions of the established rescue measures;
3) **Unconventional problem solving**: the system must be able to gather general data and information in order to exploit them with a different purpose, focused on the execution of the emergencies operations.

The developed methodological principles have been embodied into a specific system architecture, employed to provide an assistance tool during the emergency situations, both for rescuers and building occupants.

This method has not to be intended to interfere with standard rules, which have to be respected during rescue operations according to current norms. The main purpose, on the contrary, is to provide assistance during the execution of standard operations in order to gather data from the evolving environment and find real-time effective and resilient solutions in case of unforeseen events.

1.2. METHOD

The developed methodology proposes to exploit general data, which usually are not considered in the emergency management in order to extract information, which can be easily applied in order to find alternative solutions to unforeseen problems during emergencies.

The fundament of the method is a theory, which promotes the autonomy and cooperation of the involved actors in order to achieve a fast and effective result, the Holonic Theory.

By applying this theory, the limits of rigid workflows are overcome through a de-centralized structure that enables actors to react on their own on the basis of the real effective occurring situations and to cooperate one with each other to face common problems mainly due to unforeseen events. Holonic systems originate from the works of the philosopher A. Koestler [4] who in 1967 proposed the term holon to describe his observations of the behaviour of biological and social systems. The word holon itself originates from the Greek word ”holos” meaning ”whole” and the suffix ”on” meaning ”part of” i.e. a neutron or proton. He found that all biological and social systems evolve, grow, and adapt to complex and changing environments by forming stable intermediate holons. More specifically, holons exhibit a dual behaviour, which he called the Janus Effect [5]. On the one hand, each holon has an autonomous quality. Its development and functionality is sufficient to exist alone. On the other hand, each holon also has a cooperative quality that allows it to depend upon a social framework of holons. In such a way, they interact together to meet overall goals of the collective. [6] A system of holons that can cooperate to achieve a goal or objective is named “holarchy”: it defines the basic rules for cooperation for the holons and thereby limits their autonomy. [7]

This theory has been till now deeply developed and successfully applied in the sector of most customizable and variable upon request production, in order to cope with fast changing requests and scenarios, leading to the creation of Holonic Manufacturing Systems (HMS). The possibility of the actors to cooperate each other in a flexible way makes the whole system reactive to the occurring changes and consequently, the whole process workflow extremely flexible and agile.

As a fundament of this work, a similarity between the fast changes in emergencies scenarios and the custom-based production has been detected, enabling the innovative utilization of the Holonic theory as an asset in the emergency management, useful to face unforeseen events.

We have considered the application of this theory a valid method to tackle the too strict hierarchical approach that sometimes affects the success of emergency management. Since it promotes a major autonomy of the agents at the lowest level of the hierarchy in order to execute local actions and to cooperate one each other to reach common objectives, it allows avoiding the bottlenecks generated by a time consuming and inefficient top-down decision making flow.

Another important scientific contribution is represented by the concept of using general data in order to arrange rescue operations in unconventional manners. The resilience and real-time effectiveness of the system is reached by the capability of the system to react to obstacles in the normal process flow and find alternative solutions that are not usually provided by normal emergency plans also by exploiting resources that are not devoted to this purpose: from finding alternative ways out, to use unconventional means.

For this purpose, a virtual reality game engine has been selected as the proper collector of heterogeneous data to be combined together in order to extract information to be employed for the rescue aim during an emergency scenario. This environment allows integrating data deriving from different sources and of different types, topological data regarding the built environment in the most updated version and data gathered by sensors deployed on site, useful to update the evolving states of the environment during the emergency.

BIM models have been employed as provider of information concerning topology and materials of the examined spaces, since they supply comprehensive, standardized data format along with integrated process. Through specific interchange format such as IFC (Industry Foundation Class) it is possible to interface other filed software or to extract necessary information that already exist in BIM and many end-users would not be able to understand in a raw format.

Information regarding the detection of the occupancy of the spaces and the evolving of the emergency, namely the spreading of smoke in the building during a fire emergency, have been simulated through specific simulation engines.

In the same environment, it has been possible to introduce elements of Artificial Intelligence by programming virtual agents, namely the “holons”, in order to react to the unforeseen events in an effective manner, by supplying real-time information about the environment and employing unconventional resources in order to achieve the objective of escaping from the building during the emergency. Cooperation among agents allows holons to negotiate for a wider objective in order to achieve their goals with mutual support.

Alternative solutions investigated by the holons, employing the use of “unconventional” resources are evaluated by another external simulation engine, yet integrated with the virtual reality one, which selects the most suitable set of operations to execute on the basis of resources availability and relative time of execution, by the use of a “Bayesian bettor”.

In the proposed work, the virtual reality environment has represented the test bed for the holonic theory applied to the emergency management: by simulating a fire scenario, agents have been modelled in order to react to casual events in a resilient way, exploring alternative solutions to the standard ones, in case these are not executable.

A further description of the developed method is provided in section 4.

1.3. Thesis Outline

The thesis is structured as follows:

- Chapter Two presents the state of the art in the emergency management, exploring several methods that are currently applied, concluding with the selection of the reference ones.
- Chapter Three presents the Conceptual and technological framework upon which the whole work relies on:
  - The fundamental theoretical framework represented by Holonic theory and Bayesian Network is presented and described for the parts that have had an influence on the developed architecture;
  - BIM methodology and software characteristics and advantages are described;
  - An overview of the use of Virtual Reality and its employment in several Engineering fields is provided;
  - The possible uses of the technologies afferent to the emergent field of Internet of Things for emergency management are mentioned.
- Chapter Four is dedicated to the description of the developed methodology, providing first an introductive addressing of the faced issues, then a description of the methodology developed by our research group and main object of this thesis. Then, the system architecture created to embody the stated methodological principles is described.
- Chapter Five provides the description of the application of the developed methodology and system architecture to a specific case study. Outcomes about the experiment constitute the final part.
- Chapter Six is devoted to present the conclusions about the developed and tested method, along with space for future work starting points.

2. STATE OF THE ART IN THE EMERGENCY MANAGEMENT

As aforementioned, emergency management is an interesting matter of research due to its topicality in our lives and its multidisciplinary implications: from evolution of physical phenomena, to psychological and social behaviour. In this section, an overview of the actual state of the art in this subject has been reported, presenting a variety of approaches.

As follows, a brief description of the selected researches that have influenced most our work in terms of conceptual or technological approach has been reported.

2.1 IMPROVEMENT OF EMERGENCY PLANS

Emergency plans play a key role in the emergency management of buildings and infrastructures, although they remain as plain-text documents, with the consequence of inefficient administrative work such as plan generation, documentation and maintenance. Operational use of plans such as rapid knowledge retrieval and acquisition cannot be performed as well, affecting emergency training during the preparation process as well as plan review at the scene of the accident. Additionally, the knowledge codified in emergency plans is mostly depicted by texts, which are not vivid and intuitive enough to clearly convey the instructions of response procedures and relative information. [8]

Several authors have addressed this issue in the specific context of emergency management in metro operations, for the great level of complexity of these environments due to the huge volume of people involved, mainly constituted by visitors with an absent or very low level of knowledge of the metro spaces. Several authors therefore propose the use of BIM models in substitution to actual emergency plans in order to leverage the information means in case of emergencies.

As a response, Luo et al. propose an ontology-based knowledge management method along with a unified and formalized plan repository built to facilitate the efficient administrative and operational use of emergency plans.

BIM technology is applied to provide realistic visualization of the plan knowledge for better understanding. A prototype of emergency plan training system, which integrates BIM and the ontology-based plan repository, has been developed to demonstrate the feasibility and effectiveness of the method.

The ontology-based knowledge management of emergency plans for metro operation has been proposed to organize and represent the plan in a standard and semantic way, enhancing the efficiency in both administrative and operational use of emergency plans. According to the author, with this approach, the automation degree of emergency plan management will be advanced, and a collaborative environment for different parties involved in the whole lifecycle management of plans can be provided for information sharing and reuse.

The authors proposed the creation of a structured, standardized and formalized knowledge repository of emergency plans for metro operation, based on a knowledge domain extracted from the analysis of national guidance and emergency plans in several cities. In this way, it has been possible to identify the necessary information that should be included in the plan, such as response organizations, procedures and rescue resources.

Then, an ontology-based knowledge model has been built based on the concepts and relations extracted to conceptualize the identified information of emergency plans.

The administrative work has been supposed easily to achieve generating a new plan with reusable and shared template, making fraction updating without going through the whole paper and performing exact search for plan reviewing by different actors. As for its operational use, the ontology-based knowledge representation can promote computer-aided emergency management work such as high-quality staff training or timely knowledge support for decision making at the scene. [8]

2.2 Use of BIM and Virtual Reality

Recent building emergency management research has highlighted the need for the effective utilization of dynamically changing building information. BIM (Building Information Modelling) can play a significant role in this process due to its comprehensive and standardized data format and integrated process.

In several works, Wang et al. introduce a BIM based virtual environment supported by virtual reality (VR) and a serious game engine to address several key issues for building emergency management, for example, timely two-way information updating and better emergency awareness training. The focus of the research lies on how to utilize BIM as a comprehensive building information provider to work with virtual reality technologies to build an adaptable immersive serious game environment to provide real-time fire evacuation guidance. [9]

The research focuses on two key factors for emergency management: (1) timely two-way information flow and its applications during the emergency and (2) convenient and simple way to increase evacuation awareness.

By utilizing the comprehensive data resources hosted in BIM, mobile devices held by building users/visitors, coupled with the help of specific tags, a real-time two-way and dynamic information flow has been successfully created and demonstrated between the virtual environment (provided by BIM and a game engine) and a real building user. The BIM-VE (Building Information Modelling – Virtual Environment) can create real-time evacuation routes according to the real-time location of the user.

Another research target was to provide convenient training (to building users) to increase emergency awareness, allowing them to quickly get familiar with the building and identify the right evacuation route. [9]

2.3 Use of BIM and indoor positioning system

The ability to locate people quickly and accurately in buildings is critical to the success of building fire emergency response operations, and can potentially contribute to the reduction of various building fire-caused casualties and injuries. In [10], Nan Li et al. introduce an environment aware beacon deployment algorithm designed by the authors to support a sequence based localization schema for locating first responders and trapped occupants at building fire emergency scenes. The algorithm is designed to achieve dual objectives of improving room-level localization accuracy and reducing the effort required to deploy an ad-hoc sensor network, as the required sensing infrastructure is presumably unavailable at most emergency scenes. The deployment effort is measured by the number of beacons to deploy, and the location accessibility to deploy the beacons. The proposed algorithm is building information modelling (BIM) centred, where BIM is integrated to provide the geometric information of the sensing area as input to the algorithm for computing space division quality, a metric that measures the likelihood of correct room-level estimations and associated deployment effort. BIM also provides a graphical interface for user interaction.

Metaheuristics are integrated to efficiently search for a satisfactory solution in order to reduce the computational time, which is crucial for the success of emergency response operations. The robustness of the algorithm was also examined as the deployed ad-hoc sensor network is subject to various hazards at emergency scenes.

This work provides first a glance of the actual technological real-time location systems, and then proposes the developed algorithm in order to integrate RTLS (Real Time Locating Systems) and BIM models of the monitored spaces.

2.4 Implementation of artificial intelligence for emergency management

Crowds of people are often found in enclosed or constricted spaces. Evacuation in such situations is usually conducted calmly, but real or perceived danger may trigger panic. In panicked crowds, the interpersonal distance crowd members normally observe is often overwhelmed by the physical pressure of crowd members pushing against each other.

That pressure can both slow evacuation and lead to injury or death. Models have been developed to study crowd evacuation in a range of situations. In [11] Cantrell et al. propose the implementation, testing, and validation of a crowd evacuation model using Unity 3D, a commercial computer game engine. A realistic physics-based model of crowd movement that calculates and considers the physical pressure crowd members exert on each other was implemented in Unity. The implemented model was tested under both non-panicked and panicked scenarios; those tests exhibited known qualitative characteristics of such scenarios. The implementation and validation show that Unity can be an effective tool for evacuation modelling.

2.5 Holonic management in emergency scenarios

In order to respond to emerging needs for safety and security in today’s world dynamics, Ulieru et al. propose an evolutionary, adaptive risk management system with holonic and autonomic computing properties. [12]

As a holonic ecosystem of three main types of holarchies (Risk, Infrastructure and Support) which dynamically interact through inter-agent communication, the systems is capable to learn, respond and adapt to new situations much like biological organisms adapt and respond to threats in their struggle for survival. Rooted on a solid emergency response management strategy encompassing the eight dimensions of the autonomic computing paradigm, the system acts at several levels to protect critical infrastructure, by e.g. ensuring simultaneously the security of the information infrastructure, on which most of today's critical infrastructure depends.

Their focus is on protecting critical infrastructure (e.g. public utilities) which vitally depends on network and information security, providing a system that can adapt to its changing environment through its self-organizing capability.

2.6 Considerations and suggestions

In conclusion, we report our vision of the aforementioned described researchers, highlighting the aspects that have inspired us in our work, both in a critical and in a developing way.

The improvement of information means that promote a shift from static emergency plans to BIM models have been considered interesting for our purposes, for their characteristic of:

- major understandability by the evacuees and rescuers;
- capability to update the model with information about the monitored spaces deriving from sensors deployed on site;
- increased easiness in the as-built update.

The possibility to integrate BIM models with immersive virtual reality engine has been investigated and utilized with a different purpose from the one reported in [9], in order to provide the environment to apply and test the holonic theory applied to emergency management.

Real-time location systems integrated with BIM models have been retained crucial to provide updated information about a relevant aspect like the position of people trapped during an emergency. In our work, we have considered a simulation engine that simulates data deriving from distributed RTLS system into our virtual environment in order to feed it with data about people location inside the monitored spaces.

A first attempt of applying holonic theory in emergency situations has been carried out by Ulieru et al. Their research has been focused on the resilience of communication infrastructures during emergency scenarios. We have further extended this concept by promoting the application of holonic theory to a wider range of perspectives in the emergency management, concretized by the creation of an assistance tool for rescuers and evacuees according to holonic principles.

We have retained to not follow a knowledge-based approach based on a predefined set of possible scenarios, since one of the milestones of our research is the resilience of the system to unexpected events that cannot foreseen. Therefore, the whole representation of the sum of incidental events that may occur is not feasible.

3. CONCEPTUAL FRAMEWORK

In order to overcome the limits of the traditional emergency management approach, our research group has identified several reference theories and technological means to implement and test our novel approach. It provides a shift from a static, generic pre-planning and a rigid hierarchical structure to handle rescue operations, to a dynamic and more flexible one, allowing the fulfilment of greater agility in the emergency management.

The object of this chapter is the presentation of the conceptual framework within which we have implemented our methodology that is going to be debated in the next sections.

The components of our conceptual framework that are described as follows are:

1) The holonic theory as fundamental theoretical framework
2) Bayesian Network: means to face uncertainties due to unforeseen events
3) BIM models: in the meaning of technological containers of information about buildings
4) Virtual Reality for Engineering and Artificial Intelligence
5) IoT: a brief about the newest technologies belonging to the emerging field Internet of Things and how to exploit them for safety purposes.

3.1 HOLONIC THEORY

Holonic systems originate from the works of the philosopher A. Koestler [4], who in 1967 proposed the term holon to describe his observations of the behaviour of biological and social systems. The word holon itself originates from the Greek word ”holos” meaning ”whole” and the suffix ”on” meaning ”part of” i.e. a neutron or proton. He found that all biological and social systems evolve, grow, and adapt to complex and changing environments by forming stable intermediate holons. More specifically, holons exhibit a dual behaviour, which he called the Janus Effect [13] [4]. On the one hand, each holon has an autonomous quality. Its development and functionality is sufficient to exist alone. On the other hand, each holon also has a cooperative quality that allows it to depend upon a social framework of holons. In such a way, they interact together to meet overall goals of the collective [14] [15]. The temporary subsystems built up by holons in order to achieve common objectives, are defined as “holarchies”; they set the basic rules for holons’ cooperations as well as limits to their autonomy. [6]

In [13] Koestler, with a biomimetic approach, remarks the concepts of “part” and “whole”, making a comparison among “holons” and organs: each organ is a sub whole towards its subordinated parts, working as a self-contained whole, while towards its superior controls it works as a dependent part.

The theory is based upon an observed similarity among complex systems of any sort with the evolution of natural systems: according to Koestler, the term holon can be applied to any stable sub whole in an organismic, cognitive, or social hierarchy which displays rule-governed behaviour and/or gestalt constancy. Thus biological holons are self-regulating “open systems” governed by a set of fixed rules, which account for the holon’s coherence, stability and its specific pattern of structure and function. [13]

A holon consists of an information processing part and often a physical part.

A holon can be part of another holon [16]. In addition to the properties of autonomy and cooperation, some authors [17], [18], [19] add recursivity, self-organization, and reconfigurability to the list of manufacturing holon properties. These properties, upon which the holon definition rests, are also defined below.

- **Autonomy**: The capability of an entity to create and control the execution of its own plans and/or strategies [16].
- **Cooperation**: A process whereby a set of entities develops mutually acceptable plans and executes these plans [16].
- **Recursivity**: A similarity in the informational architecture and communications model between holons [17].
- **Self-Organization**: The ability of manufacturing units to collect and arrange themselves in order to achieve a production goal [16].
- **Reconfigurability**: The ability of a function of a manufacturing unit to be simply altered in a timely and cost effective manner [16].

Additionally, the holonic literature often refers to holonic attributes, and for clarity, its definition is given below.

- **Holonic Attributes**: Attributes of an entity that make it a holon. **The minimum set is autonomy and cooperation** [16].

3.1.1 Holonic Manufacturing Systems

The Holonic Manufacturing Systems (HMS) field was initiated in Japan by Suda [20], [21] as a response to the growing perception that Japanese manufacturing firms lacked competitiveness in a global manufacturing environment. He hypothesized that the cause of this inability to compete was rigid manufacturing practices that did not have the necessary agility 1 and responsiveness 2 in increasingly volatile markets. Suda noted that the robustness 3, flexibility 4, and adaptability 5 of holonic systems would be a highly desirable characteristic in the effort to regain international competitiveness.

Since that point, numerous and relevant technology contributions have been made in the field of holonic manufacturing systems. Basic definitions characterizing holonic systems are provided as follows:

- **Agility**: The quickness with which a system adapts to modifications of the production and/or product envelop in the sense of operation flexibility [16]. It is both reactive (responsive) and proactive [22].
- **Responsiveness**: the ability of a production system to respond to dynamic conditions (originating inside or outside the manufacturing organization) which impact upon production goals [23]. It forms the reactive part of agility [22].
- **Robustness**: the ability of a system to not have to respond or change its behaviour because it is designed well enough so that these disturbances do not affect the output [16].
- **Flexibility**: the facility with which a system design may be modified to meet similar product requirements [16], [24] and extended with new elements to augment the existing level of functionality [25], [24], [26].
- **Adaptability**: the ability of a system in operation to change behaviour to maintain its desired output in the presence of external and/or internal disturbances [16].

Robustness, flexibility and adaptability are necessary parts of responsive and agile systems. The first being a subset of the second [22].

It was these ideas which Suda felt would be particularly beneficial in a manufacturing system [20], [21] Soon afterwards, the Holonic Manufacturing Systems Project with its associated research consortium was formed as one of the six Intelligent Manufacturing Systems (IMS) feasibility studies [27], [7], [16], [28].

Since then, numerous conceptions (of varying degrees of similarity) were proposed to bring holonic principles to a manufacturing context. In order to instantiate more concretely such a holon, one generally accepted conceptual architecture is introduced in Figure 1. [6]

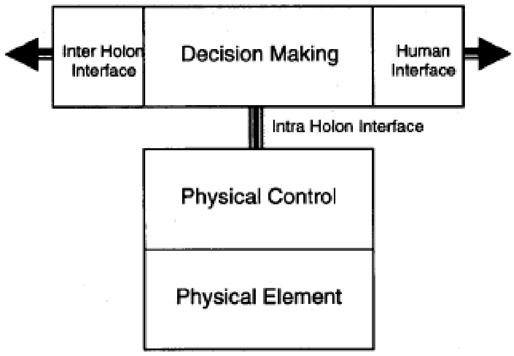


FIGURE 1. A GENERIC ARCHITECTURE OF A HOLON [29]

Holonic architectures are composed out of holons. They were introduced in the manufacturing control domain, to create systems that could better deal with current and future challenges then the existing systems. Manufacturing control is the operational level of production planning and control. It is the decision making activity concerned with the short-term and detailed assignment of operations to production resources.

Holonic architectures were introduced to provide an answer to some shortcomings in existing architectures of manufacturing control systems. Two types of architecture are frequently used, hierarchical architectures and heterarchical architectures. [30]

3.1.1.1 Hierarchical Systems

The traditional approach for the design of CIM (Computer Integrated Manufacturing) systems is the hierarchical approach [31]. The design is based on top-down approach and strictly defines the system modules and their functionality. Communication between modules is strictly defined and limited in such a way that modules communicate with their parent and child modules only. In a hierarchical architecture, modules cannot take initiative; therefore, the system is sensitive to perturbations, and its autonomy and reactivity to disturbances are weak.

The resulting architecture is very rigid and therefore expensive to develop and difficult to maintain. The agility of systems operating under this architecture low [32]. [33]

3.1.1.2 Heterarchical Systems

A system wide approach to agility was proposed with the conception of heterarchical systems [34], [35]. Several researchers, [36], [37], [38], [39], [40], [41], sought to replace the rigidity of hierarchical systems with a completely flat structure where each component exhibits full local autonomy [42]. Decision-making is made entirely locally at the point of information gathering and measurement [40]. Furthermore, each component cooperates via a negotiation procedure in the form of temporary and flexible relationships. [6]

Heterarchical architectures [43] allow for full autonomy between the components in the architecture. The cooperation between entities is arranged via an explicit negotiation procedure. (e.g. contract-net protocol) or via indirect coordination. Full local autonomy is maintained during the cooperative process.

The full autonomy of each component in combination with the negotiation algorithm meant that failures did not propagate and the system exhibited fault tolerance [37], [44]. For similar reasons, the system could adapt readily to local disturbances [42]. These results were supported both theoretically [45], as well as experimentally [46]. Additionally, developer found that complexity, measured in lines of code, was reduced [37]. Finally, the system flexibility was excellent as the negotiation algorithm and system components could be modified, removed, and added easily [42]. [6]

This architecture claims to increase robustness. Because components function autonomously, they should not fail when other components malfunction. The disadvantages of this architecture are reduced predictability of the control system and possible incompatibility issues. [30]

Heterarchical systems, however, in their full autonomy lost the ability to create and achieve global objectives [37], [47]. Furthermore, Valckenaers showed that the system can reach unstable states where small disturbances induce large disturbances elsewhere in the system [32]. Additionally, hierarchical systems are limited by the network bandwidth as network traffic can grow quickly with the number of components [48]. Finally, heterarchical systems where never industrially adopted due to their inability to achieve a predictable result [34], [35].

3.1.1.3 Holonic Systems

Holonic architectures try to combine the high and predictable performance promised by hierarchical systems with the robustness against disturbances and the agility of heterarchical systems by having characteristics of both architectures.

A holon can function on its own (as a whole), which increases robustness (as in heterarchical architectures). At the same time, it can also function as part of a bigger whole, forming a hierarchy with other holons for a certain period of time. This is a feature similar to hierarchical architectures.

To clarify holonic systems in a manufacturing context, the definition of a holonic manufacturing system is given with that of a holarchy of which HMS are composed.

- Holonic Manufacturing System: A holarchy that integrates the entire range of manufacturing activities from order booking through design, production and marketing to realize the agile manufacturing enterprise [16].
- Holarchy: A system of holons that can cooperate to achieve a goal or objective. The holarchy defines the basic rules for cooperation for the holons and thereby limits their autonomy [16]. [6]

In the industrial sector, at the end of 1980's emerged the concept of holarchies as a response to the limits observed in the most common diffused CIM (Computer Integrated Manufacturing), basically due to their complexity, since each controller requires knowledge of its neighbours below and above to maintain these fixed relationships [37].

This complexity is amplified when explicit interrelationship exception handling is written to improve fault-tolerance, defined as the ability of a system to continue to function, perhaps in a degraded state, despite the occurrence of system failures [49]. It is a necessary requirement for robustness and adaptability. Complexity also weakens fault-tolerance especially in the presence of disturbances and system modifications [50]. Additionally, CIM systems lack fault-tolerance because they are particularly sensitive to two failure modes. The failure of 1.) the controller or 2.) the communication link below it results in a paralysis of all the controllers to which they are connected [50], [51]. Finally, CIM systems exhibit poor adaptability because neither higher-level controllers have access to detailed sensory information nor lower level controllers have the computational resources to make effective use of the data [42]. As a result, data is aggregated and thereby delayed in database formation [42]. In the presence of disturbances, the optimized global decisions of higher-level controllers use obsolete or estimated data [42], [52].

The failure of heterarchical systems and the need to resolve CIM systems' deficiencies opened the way for numerous new manufacturing concepts – loosely categorized as Next Generation Manufacturing Systems. In addition to holonic manufacturing systems, other concepts like bionic [53], [54], genetic [55], [56], fractal [57], random [58], and virtual manufacturing systems [59] were proposed [60], [61].

Bongaerts and Van Brussel state that holonic systems are preferable because they emphasize autonomous holons that maintain robustness and adaptability in the presence of disturbances, loose hierarchies that permit global optimization, flexible hierarchies that are reconfigurable and adaptable and migration strategies that facilitate industrial adoption [60], [61].

The qualities of autonomous holons and loose-flexible holarchic is a fusion of the advantages of hierarchical and hierarchical systems [60]. Hierarchy is introduced to not just permit global optimization but also to create stability in the system [61] as in the watchmakers parable told in [62], [63]. At the same time, these structural relationships are neither fixed nor permanent. Holons can belong to multiple hierarchies, enter and leave them and do not rely on the proper function of their neighbours [60]. Figure 2 gives an abstracted view of a holarchy.

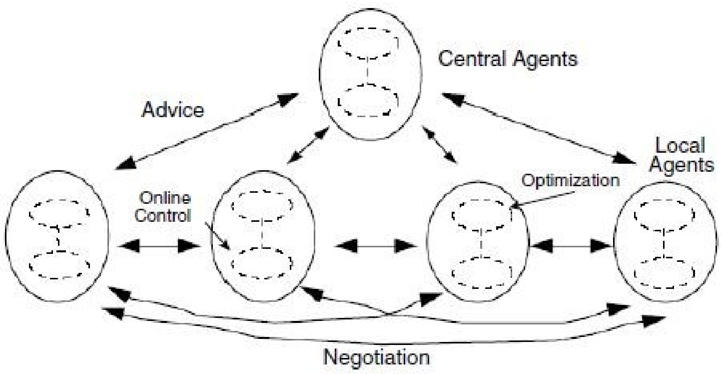


FIGURE 2. ABSTRACTED HOLARCHY STRUCTURE [34], [35]

Additionally, holonic systems have autonomous and cooperative qualities much like heterarchical systems do [18]. They negotiate amongst each other and make local decisions, albeit with less autonomy than their heterarchical system counterparts [61]. Holons that are more central also have the ability to give advice or apply flexible rules to more peripheral holons [60]. In these ways, holonic manufacturing systems can mitigate most unwanted circumstances and become robust [64], flexible and adaptable [65].

Having defined the necessary set of behavioural properties, attention can now turn to the elements of its composition, which would allow it to achieve these behaviours. A holon is necessarily composed of a physical, hardware part and a decision-making software part, which are connected by an intra-holon interface [28]. Additionally, each holon has both a holon human interface and an inter-holon interface for communication directed to achieving global objectives [29].

The physical hardware part of a holon is traditionally thought of as the manufacturing resources, which one may find in a plant such as a milling or stamping machines [16].

Their control might be a combination of programmable logic controllers (PLC), local area networks (LAN), and PC's [16]. However, this conception is not sufficient. Firstly, not any machine can be readily included into a holon architecture. Specifically, it needs to be sufficiently flexible 8 such that

1.) it may interface with the software component of the holon

2.) meet the previously specified behavioural requirements [16].

The HMS consortium has almost universally accepted that the software part of a holon and its holarchy is enabled by agents and multi-agent systems [47]. Brennan [66] explains this relationship between holons and agents in great detail and concludes that multi-agent systems are a necessary component of any HMS implementation. However, there exist many (not necessarily congruent) ideas of the definition of an agent. The author resolves the apparent disagreement with a definition formed from Huhns [67] and Durfee [68], which is found below:

- Multi-Agent Systems – Loosely-coupled network(s) of active and persistent software components that perceive, reason and communicate together to solve problems that are beyond their individual capabilities.

The reader accustomed to object-oriented programming may note that agents are similar to objects in their focus on data abstraction, encapsulation, modularity and inheritance [69].

However, they differ in that they possess a greater degree of autonomy to control their state and behaviours, can demonstrate reactive, proactive, and cooperative behaviours and have their own thread of control [70].

In [71], the difference among multi-agent systems and holonic systems is clearly depicted.

The debate on clarifying the difference between holons and agents is an ongoing issue in the research communities using these paradigms. Given the essentially different path on which each concept was developed the question, itself is inappropriate. Holarchies [15] have been envisioned as models for the Universe's self-organizing structure. On the other side, agents have been envisioned as a software paradigm aiming to expand the limitations of the static object model with proactive capabilities of autonomy and environmental awareness, the emphasis being on the interaction between software components rather than on their structure. In the sequel, we briefly present the main characteristics of the holonic and MAS – Multi Agent System paradigms [72].

Thus, holonics is an organizational paradigm (inspired by the self-organizing properties of natural systems) which models organizations as nested clusters (holons) of sub organizations (sub-holons) driven towards a common purpose by collaborative rules. The rules act as forces that coordinate interactions between sub-holons working together towards to common purpose. MAS is a software paradigm, which aims to represent dynamical systems in software by focusing on the interactions between their parts (modelled as software agents). The common denominator between holonics and MAS as paradigms is obviously the focus on the dynamics of the interactions, however in a MAS there is no pre-assigned condition that the interactions should be driven by cooperative forces, while in a holonic system this is a precondition for the existence of the holarchy per se (the glue that binds the holarchy together driving it towards the common goal.) It is this 'team-spirit' that characterizes a holarchy, in that all its component parts at all levels of resolution work together towards achieving the goal in an optimal manner.

This 'togetherness' drives the self-organizing power that configures all the sub-holons to optimize the interactions within the holarchy to reach the common goal with maximum efficiency. On the other side in a MAS agents may interact based on competitive rather than cooperative rules environments such as military scenarios; competing over resources or societal/political disputes, etc.) – which is excluded as a possibility in a holarchy.

Organizational hoarchies are real-world entities (as we exemplified before Canada as a Confederation being a political holarchy. Other examples are: a university is organized as an educational holarchy comprised of the President's offices, to which faculties (e.g. engineering, science, medicine, etc.) are directly subordinate (under a dean's leadership), to each faculty, in turn various departments (e.g. electrical engineering, manufacturing engineering, civil engineering, etc.) are subordinated under the leadership of a department head; a global enterprise is a collaborative purpose-driven/market-driven holarchy; a distributed manufacturing system is a production-driven holarchy, the organism is a survival-driven holarchy, The Universe is an evolution-driven holarchy [71]. As elements of such organizational holarchies, holons per se are by no means software entities. Thus, a 'comparison' with agents does not really make sense. In the manufacturing domain [73] however holons have been considered to be software and physical entities alike, in a cohabitation nature-software expressed through the concept of 'partial cloning' of a physical entity (either a human or a manufacturing machine/robot) as software entity which encapsulates those characteristics abstracted from the real entity needed in the particular collaborative context of the holarchy. Thus one distinguishes two ontological levels in a manufacturing holarchy, The software representation of the manufacturing holarchy enables emulation of production with distribution of the scheduled tasks on the various software agents 'cloning' the physical machines and once an optimal configuration solution has been reached the appropriate control law is deployed from the software agent on the appropriate physical machine at the appropriate time [74]. [70]

An intrinsic issue in manufacturing holarchies is thus cohabitation physical holons – software agents. In such a manufacturing co-habitation context, the concepts of holon and agent merge and software agents are regarded as holons (but not vice versa, of course). From this perspective, as a software paradigm MAS appears to be an excellent tool for emulating holarchies. A MAS, which emulates a holonic system will, consists of agents driven by a coordination mechanism designed according to the rules for cooperation of the respective holarchy. With this in mind it is easy to point that software holarchies are, specialized MAS that define the interaction between their agents based on the underlining cooperative holonic model. Such software 'holons' appear to be specialized agents which have a particular structure and holonic properties, that is they are decomposable into sub-agents which work cooperatively towards a common goal of the holarchy. Each controller requires knowledge of its neighbours below and above to maintain these fixed relationships [37].

In other words, the control system must be distributed to achieve a holon's cooperative, recursive, and reconfigurable properties.

The above requirements also directly improve adaptability. Brennan explicitly states that a distributed system can more effectively reject disturbances [66]. Adaptability is furthered by two more requirements: Time sensitive or time varying data must be used locally at the point of gathering or measurement. Time invariant data may be centralized.

Time sensitive or time varying data must be available to the relevant decision maker be they local or central, which may be generalized to the following recommendation.

The architecture of the control should be decentralized and physically based [19].

Together, these requirements and recommendations may be used to support Parunak's assertion that decentralized control must be "emergent rather than planned, concurrent rather than sequential" [75].

Requirement: Lower level controllers must have sufficient computational ability to make their designated decisions.

This requirement can be expanded to two more recommendations:

Recommendation A: The control should be both reactive and proactive [19].

Recommendation B: The control should be self-organizing [19].

One may note that this comprises a fundamental upgrade of previously held paradigms of adaptability. Not only must holons respond to disturbances, but they must also self-organize and be proactive towards achieve their global and local objectives. In this way, one may conceive the harmonization of all of the previously mentioned holon properties.

Real-time systems (in order to exist) provide not just the necessary speed but also performance predictability [76]. The execution of tasks such as robot movements can be started and finished with temporal certainty. Real-time systems also implicitly demand reliability from their components to achieve this level of predictability [77]. They can also provide the necessary adaptability by sensing and responding to unexpected events [76]. [6]

3.1.1.4 Holonic Architecture in HMS – PROSA Architecture

One of the most well proliferated conceptual architecture is called PROSA, Product, Resource, Order, Staff, Architecture. PROSA is a holonic reference architecture for manufacturing control, that has shown great potentialities to be applied also in different contexts, such as open-air engineering.

The product, resource and order holons are mandatory components of the architecture. The staff holon is an optional component. The reference architecture is designed to [78]:

– separate the necessary components, which are generic, from the optional components, which can be manufacturing system specific

– separate the structural aspects of the architecture from the algorithmic aspects for resource allocation and process planning

– separate the resource allocation aspects from process specific aspects

– foresee migration and evolution possibilities to enable the incorporation of legacy systems, or the introduction of new technology. [30]

It decomposed the shop floor into at least product, resource, and order holons as shown in Figure 3 [79].

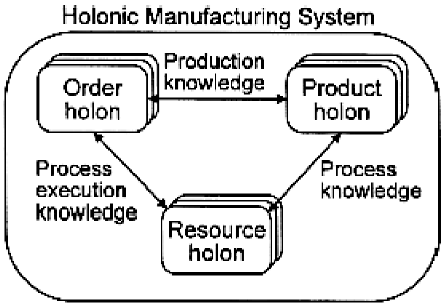


FIGURE 3. BASIC BUILDINGS BLOCKS OF PROSA ARCHITECTURE [79]

The product holon, holds the process and product knowledge required for the proper manufacture of a given product [266]. In other words, it contains the products of the traditional product design, process planning and quality assurance departments [79].

Where:

- Process knowledge is information on how to perform a certain process on a specific resource [79]
- Product knowledge is information on how to product a certain product using a specific resource [79].

The order holon represents a task in the holonic manufacturing system and manages the physical product proceeding through the system and maintains the process execution knowledge [80].

In addition to these holons, an optional staff holon may be added [60]. It provides the basic holons with supplementary information to make their decisions correctly [61]. It may be used to implement centralized algorithms deemed too difficult for a distributed solution [79]. [30]

The PROSA team in Leuven has developed companion technologies for PROSA: the delegate multi-agent system or D-MAS [81], [82], [83]. D-MAS generate short-term forecasts in a self-organising manner and allow tasks to search for solutions accounting for those forecasts. The ant-colony inspired model has been applied to the planning process in open-air engineering, a field affected by highly prevalent disturbances and variations due to the distributed nature of open air-engineering processes.

In practice, plans are generated before the process starts, based on approximate resource performance and predicted operating conditions.

Although these plans provide a good starting reference for execution, they are unable to provide the necessary visibility for continued execution of the processes, which are subject to uncertainty and variations. [30]

As a response to unforeseen events, the Research Group has introduced the concept of on-line planning, achieved by short-term operational forecasting and continuously updated with the knowledge of the actual evolving states of the processes and resources. This mechanism enhances visibility at the execution level and allows responsiveness to unforeseen events. Furthermore, thanks to the short-term forecasts, the effect of planning decisions on the process can be foreseen and the plans can be adapted proactively.
The agents employed in the architecture are defined in the following.

A **resource agent** corresponds to a resource in the underlying processing environment, which it reflects in the planning system. A resource, in the planning environment, is an entity characterized by its utility, quantity and availability in a processing environment. In an open-air engineering process, the resources include both moving as well as stationary physical entities, i.e. the work vehicles and the work site respectively.

A **product agent** corresponds to a process recipe and contains technical knowledge along with the quality requirements of a process. It holds details about how to execute a process with a sufficient level of accuracy. In a processing system, the product agent specifies a valid sequence of operations.

It also provides operation details to the resources and evaluates the quality of execution.

An **order agent** corresponds to the tasks or processes that need to be executed. It ensures that the process is completed in time and all its requirements are fulfilled.

The order agent consults the product agent to manage the execution of operations by the resources.

The on-line planning is achieved through interactions between the system agents. The product agent and the resource agent share the process knowledge, i.e. the operating information to perform operations with the resources. The order agent and the product agent share the production knowledge, i.e. the procedure to complete a process with a sufficient level of accuracy. The order agent and the resource agent share the process execution knowledge, i.e. the information about the execution of operations. For coordination purposes, the system uses the D-MAS coordination mechanism.

Two types of delegate ant agents are used, namely **exploring ant agent** and **intention ant agent**. They facilitate information exchange among the basic system agents during planning and execution. Details of the ant colony inspired coordination mechanism are provided by [81]. [30]

The PROSA architecture and the delegate multi-agent system can be successfully applied to achieve the goals of on-line planning for open-air engineering processes.

Effective planning for these processes requires a dynamic and on-line planning approach. An important requirement for on-line planning is the availability of runtime information to improve process visibility for better-informed decision-making.

The on-line planning system generates a detailed schedule of the operations for the cooperating resources. It detects the execution level disturbances and variations, and adapts the plan for the ongoing as well as the remaining operations of the process.

The system implemented according to the PROSA architecture is model-driven. With these models, the delegate multi-agent system coordination pattern models the operations and generates short-term operational forecasts. These forecasts allow foreseeing problems and opportunities at the execution level and provide sufficient information for adapting the plans according to the prevailing situations.

Because of the model-driven nature where the models support virtual execution, the system is generically applicable to other open-air engineering processes. The required models correspond to operations and encapsulate the domain-specific aspects. The success of the use of this system for an open-air engineering processes is however also dependent on proper modelling of the underline operations of the process. [84] [30]

3.2 Bayesian Network

Bayesian Network constitute a powerful mean to represent phenomena affected by a high level of uncertainty. They are a type of probabilistic graphical model that uses Bayesian inference for probability computations. Bayesian networks aim to model conditional dependence, and therefore causation, by representing conditional dependence by edges in a directed graph. Through these relationships, one can efficiently conduct inference on the random variables in the graph through the use of factors. [85]

In their easier acceptance, the Bayesian networks are graphical representations of probabilistic models. In a Bayesian Network, individual events or subsets of events are described using random variables, which, in turn, are represented graphically through nodes.

Each node has then a domain and a probability distribution that represents the probability of the occurrence of any event associated with the variable.

The domain of a node can be numeric or symbolic. The numerical domains can be continuous, comprising the whole of the real axis, or of discrete, i.e. represented through a set of numerical ranges. In a Bayesian network, the set of nodes represents the universe of events U.

As for the general case probabilistic inference, a Bayesian network allows to create a model of the universe of events describing the relationships between the individual events.

In the case of Bayesian network relationships are described by a set of conditional probability distributions. Each direct conditional dependence between variables is graphically represented by a directed arc that starts from the conditional variable and ends in the conditioning variable. The distributions are built in the most efficient way, using where possible the properties of conditional independence.

Therefore, the topology of a Bayesian Network is that of a directed acyclic graph, that is, a graph with directed edges where there are no sequences of directed edges that start at a node and return to the same node.

Deepen these concepts through a simple medical example, in which the universe of possible events is represented by a combination of three situations: having toothache, having a caries, the fact that the probe of the dentist reveals a hole in the tooth.

For the calculation of probabilistic each event can be represented by a variable that takes the value true if the event occurs and the value false otherwise.

Therefore, we introduce three variables: *toothache*, *cavity* and *catch* for the situation related to the probe of the dentist, with the meaning that, for example
toothache = true is the event of having toothache, and toothache = false is the
event of not having toothache.
The simplest form of representation (model) of this fragment of reality is to assign a probability value relatively to the occurrence of each possible combination of events.
The values can be tabulated in a table called joint probability table. The only requirement to be met for the moment is related to the probability and requires that the assigned probabilities compound to 1.

		Toothache				_Toothache	
	Catch		_Catch		Catch		_Catch
Cavity	0.108		0.012		0.072		0.008
_Cavity	0.016		0.064		0.144		0.576

FIGURE 4. JOINT PROBABILITY TABLE FOR MEDICAL EXAMPLE

Considering the above example, the universe of events was represented through the three random variables: toothache, cavity, catch. The probabilistic model, originally defined by the joint probability distribution, is defined in the Bayesian network, using the distribution of conditional probability. In our example, we have seen that toothache and catch both are caused by caries, but none has a direct effect on the other. This conditional independence allows us to decompose the joint probability distribution P (toothache, cavity, catch) in three parts:
- P (Cavity) the a priori probability on the fact of having caries
- P (Toothache/Cavity) the probability of having toothache conditioned to the fact of having caries
- P (Catch/Cavity) the probability that the probe of the dentist reveals a cavity in the tooth conditioned to the fact of having caries
To this decomposition corresponds a network structured as shown in Fig. 5.

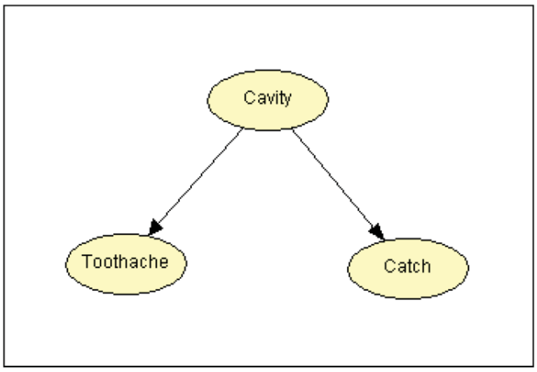


FIGURE 5.BAYESIAN NETWORK REPRESENTATION FOR THE PROBLEM OF TOOTHACHE. THE NODES

Alternatively, you can build the same network using the relation of cause - effect. This can be done by asserting that Cavity is the direct cause of both of Toothache and Catch, and that there is no causal relationship between the latter relates.

In the example, nodes represent random variables of type boolean. They can be a value from the only two possibilities: (true, false). These variables therefore represent individual events.

Each node has a probability distribution that defines the probability value for each single value of the domain of the node. The nodes that have no incoming edges (Cavity in this case) are called root nodes. For them, the probability distribution is defined as a priori probability of the event relative to the node, in this case P (Cavity), while for the other nodes in the distribution is a conditional distribution, in this case P (Toothache / Cavity) and P (Catch / Cavity). The values related to the distribution can be derived from the table in our example joint probability according as said.

Thus, we have:

P (Cavity) = 0.2

P (Toothache/Cavity) = 0.12/0.2=0,6, P (Toothache/-Cavity) = 0.08/0.8=0.1

P (Catch/Cavity) = 0.18/0.2=0.9, P (Catch/-Cavity) = 0.16/0.8=0.2

This complete the Bayesian model example of toothache because missing values are calculated as a complement to one. Notice how it was necessary to determine only five of the eight values instead of the joint probability table, thus saving about 37% of the data. This is one of the main advantages of Bayesian networks, the ability to build probabilistic models in a highly efficient way. The other advantage resides in the possibility of constructing the global network as a composition of local models.

The Bayesian model thus constructed is perfectly equivalent to the model defined by the joint probability table, and allows to perform the same type of inferences. The initial network allows evaluating the probability of each event.

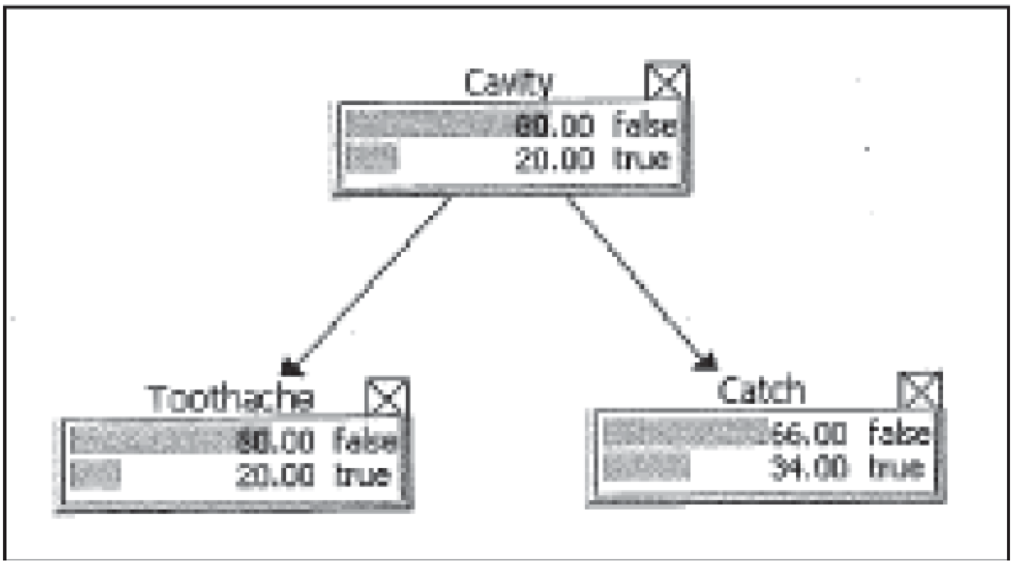


FIGURE 6. PROBABILITY DISTRIBUTION OF THE NETWORK NODES IN THE BAYESIAN

The network also allows to perform Bayesian inference type, that is, to update the probability distributions of the nodes downstream of the observation of one or more events. In Bayesian, networks observe an event means to place the relative probability equal to one. The conditional probability P (Toothache / Cavity) can thus be easily assessed by observing the event Cavity. The node Toothache 0.60 shows the value similar to that calculated from the joint probability table. Obviously, the network, downstream of an observation, calculates the conditional probability for all other events.

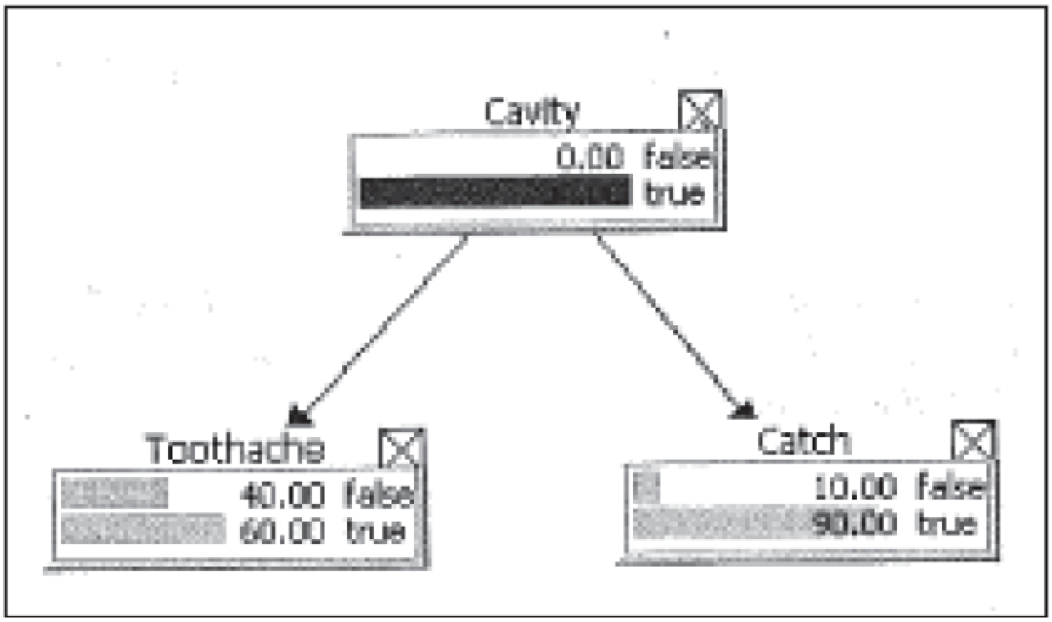


FIGURE 7. DISTRIBUTIONS OF CONDITIONAL PROBABILITY OF OCCURRENCE "CAVITY" IN THE BAYESIAN NETWORK OF THE PROBLEM RELATED TO TOOTHACHE.

The probability of a joint event, for example P (Toothache ^ Cavity), can be evaluated using the formula of probability of conditioned probability as: P (Toothache ^ Cavity) = P (Toothache / Cavity) x P (Cavity) = 0.6 x 0.2 = 0.12

Finally, the property of conditional independence: P(Toothache ^ Catch / Cavity) = P (Toothache / Cavity) P (Catch / Cavity) can be highlighted verifying that, downstream of the observation of the node conditioning (Cavity), changing the value of probability of one of the nodes conditioned, the probability distribution of the other does not change.

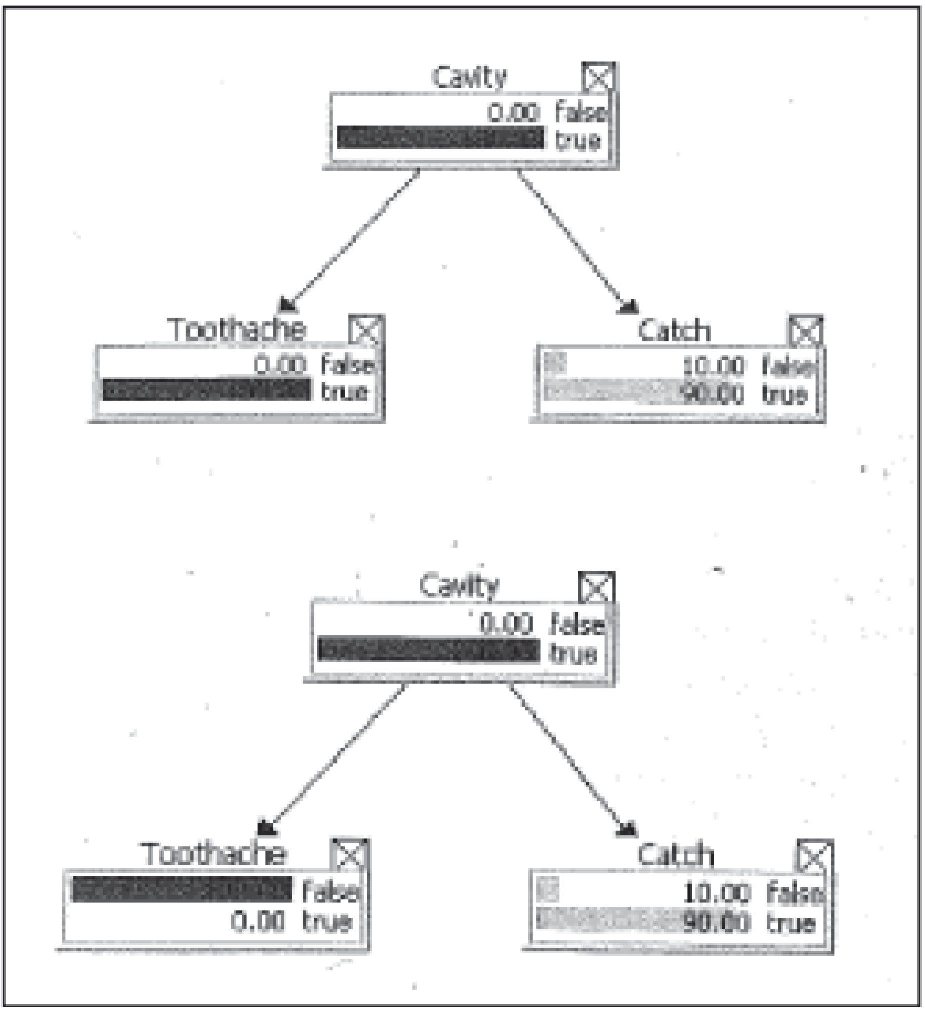


FIGURE 8 EXAMPLE OF CONDITIONAL INDEPENDENCE. DOWNSTREAM OF THE OBSERVATION OF THE NODE "CAVITY", THE VARIATION OF THE PROBABILITY DIST IBUTION OF NODE "TOOTHACHE" HAS NO EFFECT ON THE PROBABILITY DISTRIBUTION OF NODE "CATCH"

3.2.1 CONDITIONAL INDEPENDENCE

Due to the Bayesian network, you can define some criteria to determine topological conditional independence between the nodes:

A node is conditionally independent of its non-descendants starting from its parents.

Markov Blanket: a node is conditionally independent of the other nodes in the network starting from his parents, his children and the parents of his children.

D-separation: is a general topological criterion that determines whether a set of nodes X is independent of another set Y given a third set Z. In order to verify this condition is necessary to check whether the set of nodes Z blocks every path from node X to node Y.

The path is a sequence of consecutive arcs and of any direction in the network graph. The d-separation is therefore the more general topological property of the networks to verify the condition of conditional independence between groups of nodes. This principle rule, in fact, the algorithms of calculation of the networks. The algorithm for the calculation of the d-separation is somewhat cumbersome and not indispensable for the understanding of the arguments.

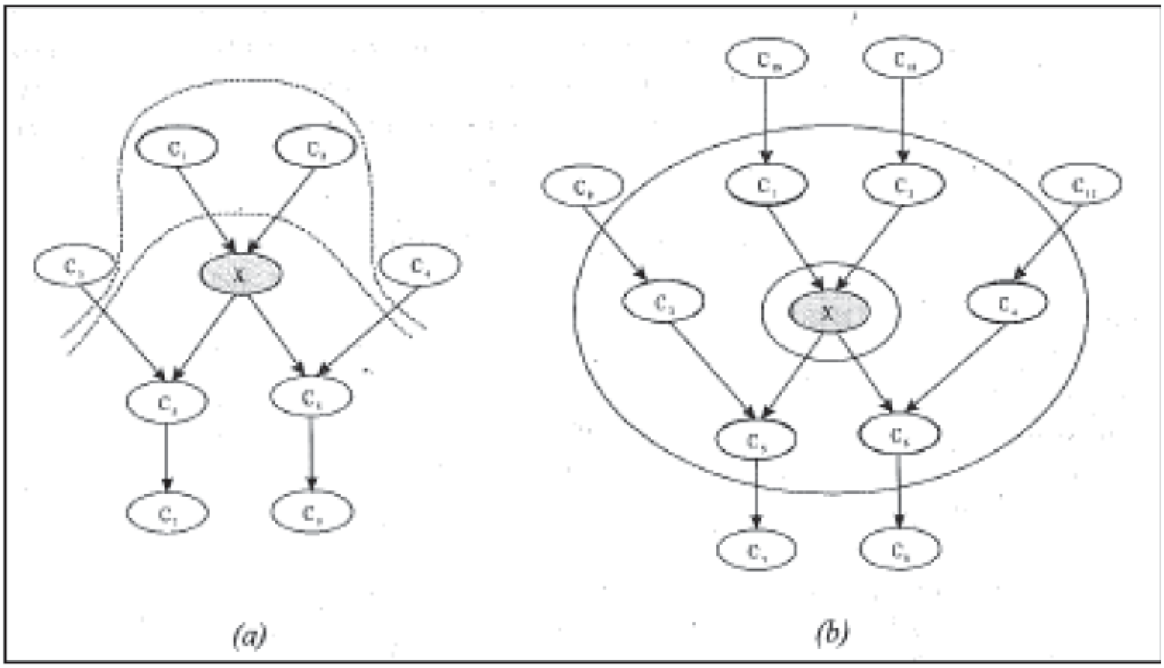


FIGURE 9. CRITERIA TOPOLOGICAL CONDITIONAL INDEPENDENCE: (A) X IS INDEPENDENT OF C3 AND C4 DATA C1 AND C2 (B) X IS CONDITIONALLY INDEPENDENT OF C7, C8, C9, C10, C11, C12 DATA C1, C2, C3, C4, C5, C6

We have just seen how to derive the formulation of the Bayesian network from the most general form possible of the probabilistic model: the joint probability distribution.
This process, although strict, is not the only effect and the simpler to reach the construction of a network. In general, a Bayesian network can be built in three alternative ways:

- **Total Direct Synthesis**: direct implementation of the nodes, the structure of conditional independence relations and probability distributions.
- **Partial Direct synthesis**: direct implementation of the nodes, the structure of conditional independence relations and estimation of the probability distributions through statistical learning techniques.
- **Indirect Synthesis** (structural learning): Estimation of the nodes, the structure of conditional independence relations and probability distributions using statistical learning techniques.

3.2.2 Inferences

The inference in Bayesian networks is a particular form of probabilistic inference and allows the estimation of the distributions of posterior probability a subset of nodes, given the knowledge of the probability distributions of a second subset disjoint from the first.
A Bayesian network, in general, calculates the value of the probability distribution of the individual nodes starting from the probability distribution a priori attributed to root nodes and the conditioned probability distributions relative to the other nodes.
In the example of burglary alarm, represented in the following figure, we can read the probability distributions of each node. The most interesting aspect of the inference through networks occurs when changing the probability distribution of a node of the network.

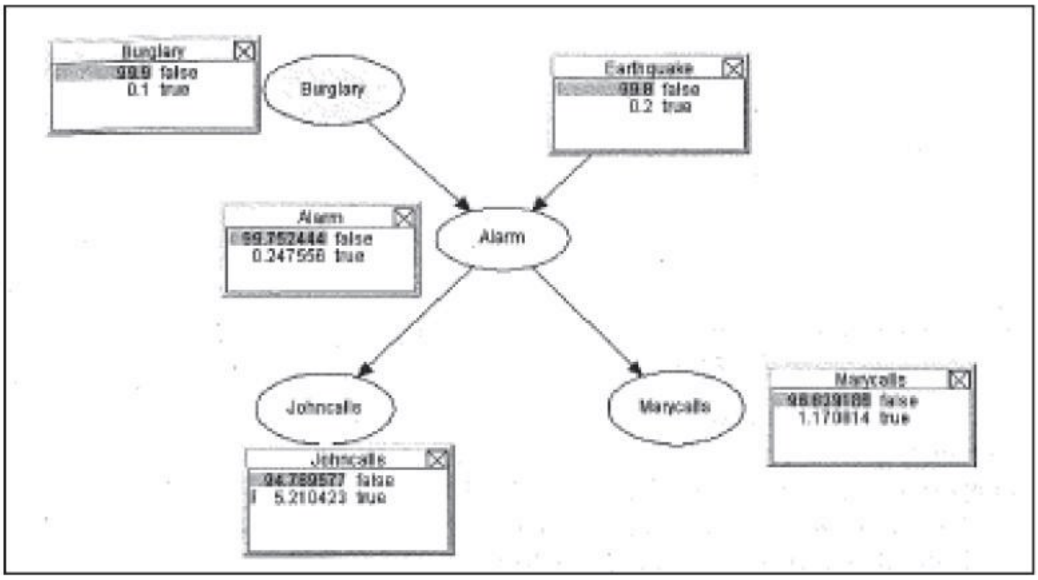


FIGURE 10. BAYESIAN NETWORK RELATED TO THE EXAMPLE OF THE BURGLARY

From a computational standpoint, a Bayesian network maintains coherence of the probability distributions of the various nodes, according to the distributions of expressed by conditioned probability relations. Therefore, if for some reason, a probability value of a variable changes, the network propagates the effects of this change to all the other nodes, as a function of the relationships that connect them. The simplest change of the probability distribution of a node consists of the observation of the event relative to the node. In the inference, Bayesian a node is said to be noted when you have full assurance of his state.

Observed node has a probability distribution in which only one, among the possible values, has a probability equal to one. The observation of the state of a node involves the updating of the probability distributions of all the other nodes.

For example, the observation of Earthquake node in the network of Figure 11 causes the updating of all nodes in the network that are conditionally dependent from it, as shown in the following figure:

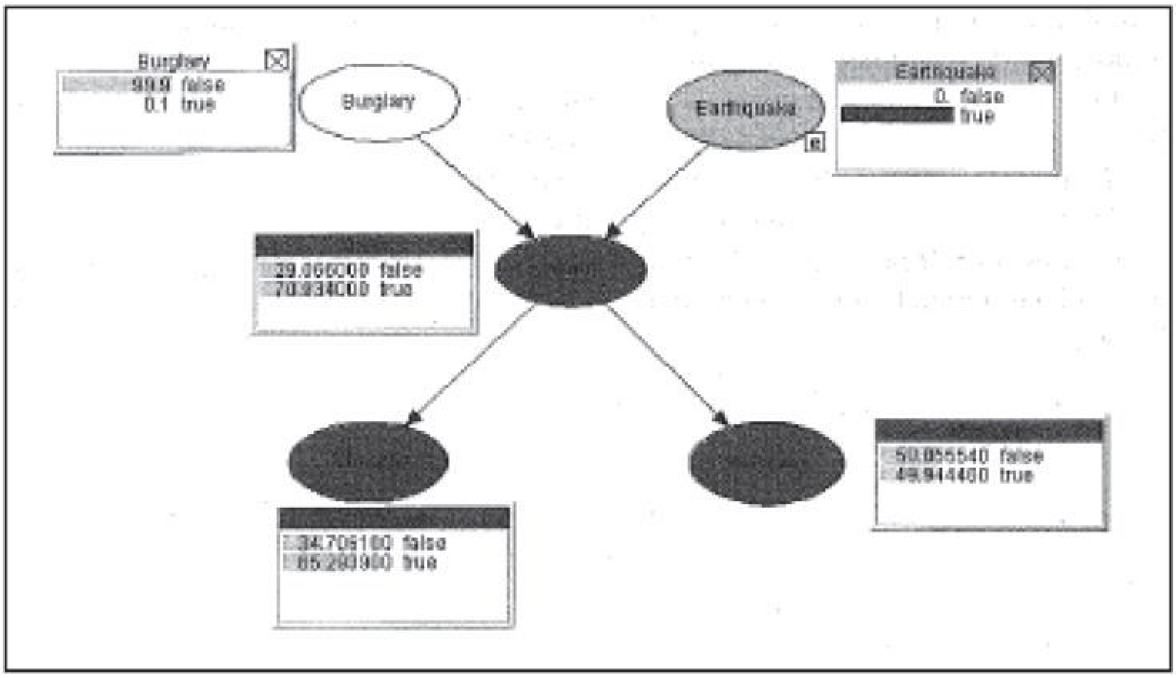


FIGURE 11. BAYESIAN NETWORK RELATED TO THE EXAMPLE OF THE BURGLARY ALARM. THE OBSERVATION OF THE NODE EARTHQUAKE CAUSES THE UPDATING OF PROBABILITY DISTRIBUTIONS OF ALL NODES IN THE NETWORK CONDITIONALLY DEPENDENT (IN DARK GREY).

The observation can be made for one or more nodes of any network. So, depending on the position of the nodes observed, it is possible to simulate some important types of logical inference:

- **Diagnostic Reasoning**: it is also called back inference (it is a form of induction) and consists of the observation of a leaf node (that has no children) and in the evaluation of possible causes, analysing the chain from parent nodes to the root nodes (those that do not have parents). The reasoning that proceeds from symptoms to causes, considering the probable causes of a particular symptom.
- **Predictive reasoning or inference**: it is also called forward inference, the observed nodes are root nodes (that nodes that have no parents) and it is evaluated the impact on leaf nodes (that nodes that have no children). Assuming to have some information about the state of other variables mentioned as effects, which follow in the direction of the arcs through the network.
- **Inter-causal reasoning**: in the case where a node C has two or more parents, the observation of the value in the node C and of one or more of its parents causes the updating of the probability of the remaining nodes parents. If there are two reasons that may have generated the same effect, the evidence of a cause and effect that change the probability of the occurrence of the other cause.

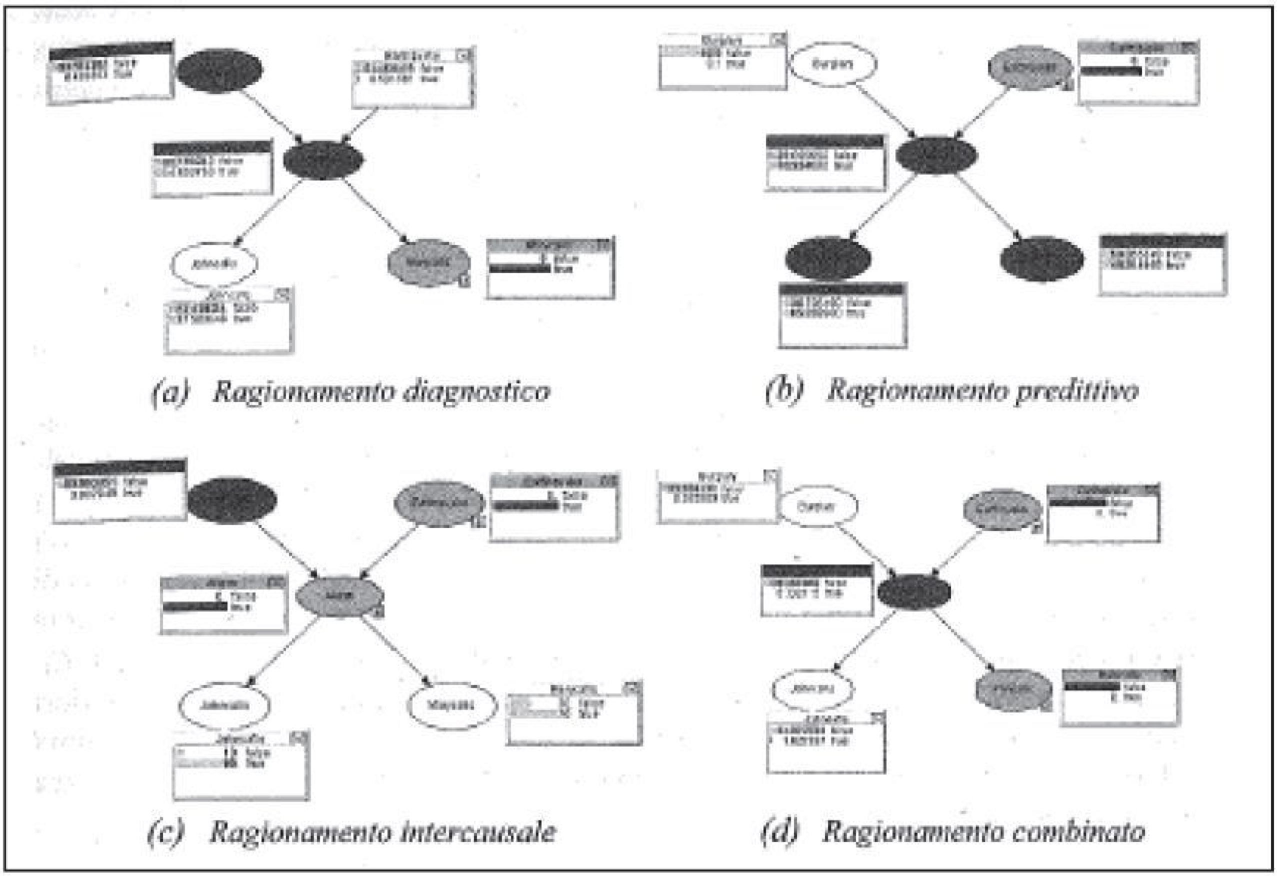


FIGURE 12. MODELS OF INFERENCE WITH BAYESIAN NETWORKS

3.2.3 Dynamic Bayesian Networks

Bayesian Networks (BN) have the unique capability to provide both intuitive and scientifically rigorous representations of complex systems. In addition, after validation, they can be used for performing both scenario analyses, through inference propagation algorithms, and diagnostic reasoning, through backward propagation based on the inversion rule. These networks also have the advantage of enabling qualitative and explicit representation, where nodes represent variables and arcs represent quantitative relationships among the same, worked out through parametric probabilistic models. When the domains to be modelled are very complex, Object Oriented Bayesian Networks (OOBN) are usually used: they are made up of several elementary networks, sharing some of the variables, which constitute the links between the networks. Each elementary network is generally developed separately (and models one of the involved many physical phenomena) but the inference algorithms are propagated over the whole set of elementary networks.

Dynamic Bayesian Networks (DBN) are used to represent statistical models that depends on time, usually called stochastic processes. DBN are based on a discretized time line, and are made up of several time slices, each representing a snapshot of the state of the system at a particular moment in time.

Transition relationships among different state variables in different time slices capture the system temporal dynamic. The application of BNs to model the evolution of processes that have temporal dynamics requires, in its simplest formulation: an initial instance of the Bayesian network that contains the formulation of the problem at time t=0, that is the set of random variables Xi,0 and the related conditional probability distributions: P(Xi,0|Xi-1,0), P(Xi-1,0|Xi-2,0), etc.; one or more transition networks that correlate the variables of the BN instance at t=0 with the variables of the BN instance at t=1.

Fig. 13 shows a graphical representation of three time slices of a DBN.

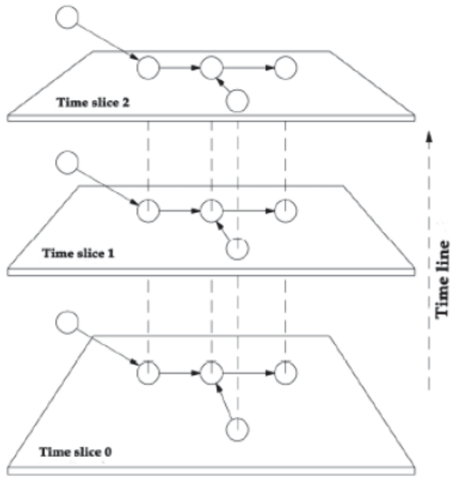


FIGURE 13. GRAPHICAL REPRESENTATION OF A GENERAL DYNAMIC BAYESIAN NETWORK: IT IS MADE UP OF THREE INSTANCES OF THE SAME BN.

Two assumptions are usually made about the physical processes at hand:

1) all the information needed to predict the state of the process at time t+1 is contained in the description of the process state at time t. No information about earlier time is needed. These kinds of processes are called Markov processes of order one;
2) the process is steady, that is, the transition networks remain the same for any ti → ti+1. [86]

3.3 BIM MODELS

The aim of this section is providing a description of BIM models, since they have constituted an important resource in our system architecture. After giving a glance of BIM, a description of the main characteristics of BIM models and their interoperability is supplied. All the contents are derived from the milestone of the matter, the BIM Handbook by Eastman et al. [87] in 2008 version.

3.3.1 INTRODUCTION TO BIM

Building Information Modelling (BIM) is one of the most promising developments in the architecture, engineering and construction (AEC) industries.

With BIM technology, an accurate virtual model of a building is constructed digitally. When completed, the computer - generated model contains precise geometry and relevant data needed to support the construction, fabrication, and procurement activities needed to realize the building.

BIM also accommodates many of the functions needed to model the lifecycle of a building, providing the basis for new construction capabilities and changes in the roles and relationships among a project team. When implemented appropriately, BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration.

All CAD systems generate digital files. Older CAD systems produce plotted drawings. They generate files that consist primarily of vectors, associated line - types, and layer identifications. As these systems were further developed, additional information was added to these files to allow for blocks of data and associated text. With the introduction of 3D modelling, advanced definition and complex surfacing tools were added.

As CAD systems became more intelligent and more users wanted to share data associated with a given design, the focus shifted from drawings and 3D images to the data itself. A building model produced by a BIM tool can support multiple different views of the data contained within a drawing set, including 2D and 3D. A building model can be described by its content (what objects it describes) or its capabilities (what kinds of information requirements it can support). The latter approach is preferable, because it defines what you can do with the model rather than how the database is constructed (which will vary with each implementation).

3.3.2 BIM – New tools and processes

As defined in BIM Handbook, BIM is as a modelling technology and associated set of processes to produce, communicate, and analyse *building models.* Building models are characterized by:

- **Building components** that are represented with intelligent digital representations (objects) that 'know' what they are, and can be associated with computable graphic and data attributes and parametric rules.
- **Components that include data that describe how they behave,** as needed for analyses and work processes, e.g., take off, specification, and energy analysis.
- **Consistent and non-redundant data** such that changes to component data are represented in all views of the component.
- **Coordinated data** such that all views of a model are represented in a coordinated way.

The following is a definition of BIM technology provided by the M.A. Mortenson Company, a construction-contracting firm that has used BIM tools extensively within their practice (Campbell 2006).

Mortenson's Definition of BIM Technology: BIM has its roots in computer-aided design research from decades ago, yet it still has no single, widely accepted definition. We at the M.A. Mortenson Company think of it as "an intelligent simulation of architecture." To enable us to achieve integrated delivery, this simulation must exhibit six key characteristics. It must be:

- Digital,
- Spatial (3D),
- Measurable (quantifiable, dimensionable, and queryable),
- Comprehensive (encapsulating and communicating design intent, building performance, constructability, and include sequential and financial aspects of means and methods),

- Accessible (to the entire AEC/ owner team through an interoperable and intuitive interface), and
- Durable (usable through all phases of a facility's life).

The concept of parametric objects is central to understanding BIM and its differentiation from traditional 2D objects. Parametric BIM objects are defined as follows:

- consist of geometric definitions and associated data and rules.
- geometry is integrated non-redundantly, and allows for no inconsistencies.

When an object is shown in 3D, the shape cannot be represented internally redundantly, for example as multiple 2D views. A plan and elevation of a given object must always be consistent. Dimensions cannot be 'fudged'.

Parametric rules for objects automatically modify associated geometries when inserted into a building model or when changes are made to associated objects. For example, a door will fit automatically into a wall, a light switch will automatically locate next to the proper side of the door, a wall will automatically resize itself to automatically butt to a ceiling or roof, etc.

Objects can be defined at different levels of aggregation, so we can define a wall as well as its related components. Objects can be defined and managed at any number of hierarchy levels. For example, if the weight of a wall subcomponent changes, the weight of the wall should also change.

Objects rules can identify when a particular change violates object feasibility regarding size, manufacturability, etc. objects have the ability to link to or receive, broadcast or export sets of attributes, e.g., structural materials, acoustic data, energy data, etc. to other applications and models.

Technologies that allow users to produce building models that consist of parametric objects are considered BIM authoring tools.

Open interfaces should allow for the import of relevant data (for creating and editing a design) and export of data in various formats (to support integration with other applications and workflows). There are two primary approaches for such integration:

(1) to stay within one software vendor's products or (2) to use software from various vendors that can exchange data using industry supported standards. The first approach allows for tighter integration among products in multiple directions. For example, changes to the

architectural model will generate changes to the structural model, and vice versa. This requires, however, that all members of a design team use software provided from the same vendor.

The second approach uses either proprietary or open - source, publicly available, and supported standards created to define building objects (Industry Foundation Classes or IFCs). These standards may provide a mechanism for interoperability among applications with different internal formats. This approach provides more flexibility at the expense of reduced interoperability, especially if the various software programs in - use for a given project do not support the same exchange standards. This allows objects from one BIM application to be exported from or imported into another.

Benefits of BIM

BIM technology can support and improve many business practices. Although the AEC/FM (Facility Management) industry is in the early days of BIM use, significant improvements have already been realized (compared to traditional 2D CAD or paper - based practices). Though it is unlikely that all of the advantages discussed below are currently in use, we have listed them to show the entire scope of changes that can be expected as BIM technology develops.

3.3.2.1 Pre - Construction Benefits to Owner

Concept, Feasibility and Design Benefits

Before owners engage an architect, it is necessary to determine whether a building of a given size, quality level, and desired program requirements can be built within a given cost and time budget, i.e. can a given building meet the financial requirements of an owner. If these questions can be answered with relative certainty, owners can then proceed with the expectation that their goals are achievable. Finding out that a particular design is significantly over budget after a considerable amount of time and effort has been expended is wasteful.

An approximate (or macro) building model built into and linked to a cost database can be of tremendous value and assistance to an owner.

Increased Building Performance and Quality

Developing a *schematic model* prior to generating a *detailed building model* allows for a more careful evaluation of the proposed scheme to determine whether it meets the building's functional and sustainable requirements. Early evaluation of design alternatives using analysis/simulation tools increases the overall quality of the building.

3.3.2.2 Design Benefits

Earlier and More Accurate Visualizations of a Design

The 3D model generated by the BIM software is designed directly rather than being generated from multiple 2D views. It can be used to visualize the design at any stage of the process with the expectation that it will be dimensionally consistent in every view.

Automatic Low - Level Corrections When Changes Are Made to Design

If the objects used in the design are controlled by parametric rules that ensure proper alignment, then the 3D model will be constructible. This reduces the user 's need to manage design changes (see Chapter 2 for further discussion of parametric rules).

Generate Accurate and Consistent 2D Drawings at Any Stage of the Design

Accurate and consistent drawings can be extracted for any set of objects or specified view of the project. This significantly reduces the amount of time and number of errors associated with generating construction drawings for all design disciplines. When changes to the design are required, fully consistent drawings can be generated as soon as the design modifications are entered.

Earlier Collaboration of Multiple Design Disciplines

BIM technology facilitates simultaneous work by multiple design disciplines. While collaboration with drawings is also possible, it is inherently more difficult and time consuming than working with one or more coordinated 3D models in which change - control can be well managed. This shortens the design time and significantly reduces design errors and omissions. It also gives earlier insight into design problems and presents opportunities for a design to be continuously improved. This is much more cost effective than waiting until a design is nearly complete and then applying value engineering only after the major design decisions have been made.

Easily Check against the Design Intent

BIM provides earlier 3D visualizations and quantifies the area of spaces and other material quantities, allowing for earlier and more accurate cost estimates.

For technical buildings (labs, hospitals, etc.), the design intent is often defined quantitatively, and this allows a building model to be used to check for these requirements. For qualitative requirements (this space should be near another, etc.), the 3D model can support automatic evaluations.

Extract Cost Estimates during the Design Stage

At any stage of the design, BIM technology can extract an accurate bill of quantities and spaces that can be used for cost estimation. In the early stages of a design, cost estimates are based primarily on the unit cost per square foot. As the design progresses, more detailed quantities are available and can be used for more accurate and detailed cost estimates. It is possible to keep all parties aware of the cost implications associated with a given design before it progresses to the level of detailing required of construction bids. At the final stage of design, an estimate based on the quantities for all the objects contained within the model allows for the preparation of a more accurate final cost estimate. As a result, it is possible to make better informed design decisions regarding costs using BIM rather than a paper - based system.

Improve Energy Efficiency and Sustainability

Linking the building model to energy analysis tools allows evaluation of energy use during the early design phases. This is not possible using traditional 2D tools, which require that a separate energy analysis be performed at the end of the design process thus reducing the opportunities for modifications that could improve the building's energy performance. The capability to link the building model to various types of analysis tools provides many opportunities to improve building quality.

3.3.2.3 Construction and Fabrication Benefits

Synchronize Design and Construction Planning

Construction planning using 4D CAD requires linking a construction plan to the 3D objects in a design, so that it is possible to simulate the construction process and show what the building and site would look like at any point in time. This graphic simulation provides considerable insight into how the building will be constructed day - by - day and reveals sources of potential problems and opportunities for possible improvements (site, crew and equipment, space conflicts, safety problems, etc.). This type of analysis is not available from paper bid documents. It does, however, provide added benefit if the model includes temporary construction objects such as shoring, scaffolding, cranes, and other major equipment so that these objects can be linked to schedule activities and reflected in the desired construction plan.

Discover Design Errors and Omissions before Construction (Clash Detection)

Because the virtual 3D building model is the source for all 2D and 3D drawings, design errors caused by inconsistent 2D drawings are eliminated. In addition, because systems from all disciplines can be brought together and compared, multi - system interfaces are easily checked both systematically (for hard and soft clashes) and visually (for other kinds of errors). Conflicts are identified before they are detected in the field. Coordination among participating designers and contractors is enhanced and errors of omission are significantly reduced. This speeds the construction process, reduces costs, minimizes the likelihood of legal disputes, and provides a smoother process for the entire project team.

React Quickly to Design or Site Problems

The impact of a suggested design change can be entered into the building model and changes to the other objects in the design will automatically update.

Some updates will be made automatically based on the established parametric rules. Additional cross system updates can be checked and updated visually.

The consequences of a change can be accurately reflected in the model and all subsequent views of it. In addition, design changes can be resolved more quickly in a BIM system because modifications can be shared, visualized, estimated, and resolved without the use of time - consuming paper transactions. Updating in this manner is extremely error - prone in paper - based systems.

Use Design Model as Basis for Fabricated Components

If the design model is transferred to a BIM fabrication tool and detailed to the level of fabrication objects (shop model), it will contain an accurate representation of the building objects for fabrication and construction. Because components are already defined in 3D, their automated fabrication using numerical control machinery is facilitated. Such automation is standard practice today in steel fabrication and some sheet metal work. It has been used successfully in precast components, fenestration and glass fabrication. This allows vendors world - wide to elaborate on the model, to develop details needed for fabrication and to maintain links that reflect the design intent. This facilitates offsite fabrication and reduces cost and construction time. The accuracy of BIM also allows larger components of the design to be fabricated offsite than would normally be attempted using 2D drawings, due to the likely need for onsite changes (rework) and the inability to predict exact dimensions until other items are constructed in the field.

Better Implementation and Lean Construction Techniques

Lean construction techniques require careful coordination between the general contractor and subs to ensure that work can be performed when the appropriate resources are available onsite. This minimizes wasted effort and reduces the need for onsite material inventories. Because BIM provides an accurate model of the design and the material resources required for each segment of the work, it provides the basis for improved planning and scheduling of subcontractors and helps to ensure just - in - time arrival of people, equipment, and materials. This reduces cost and allows for better collaboration at the job site.

Synchronize Procurement with Design and Construction

The complete building model provides accurate quantities for all (or most, depending upon level of 3D modelling) of the materials and objects contained within a design. These quantities, specifications, and properties can be used to procure materials from product vendors and subcontractors (such as precast concrete subs).

3.3.2.4 Post Construction Benefits

Better Manage and Operate Facilities

The building model provides a source of information (graphics and specifications) for all systems used in a building. Previous analyses used to determine mechanical equipment, control systems, and other purchases can be provided to the owner, as a means for verifying the design decisions once the building is in use. This information can be used to check that all systems work properly after the building is completed.

Integrate with Facility Operation and Management Systems

A building model that has been updated with all changes made during construction provides an accurate source of information about the as - built spaces and systems and provides a useful starting point for managing and operating the building. A building information model supports monitoring of real – time control systems, provides a natural interface for sensors and remote operating management of facilities. Many of these capabilities have not yet been developed, but BIM provides an ideal platform for their deployment.

3.3.3 BIM – Interoperability

No single computer application can support all of the tasks associated with building design and production. *Interoperability* depicts the need to pass data between applications, allowing multiple types of experts and applications to contribute to the work at hand. Interoperability has traditionally relied on file-based exchange formats, such as DXF (Drawing eXchange Format) and IGES that exchange only geometry.

Starting in the late 1980s, *data models* were developed to support *product* and *object model* exchanges within different industries, led by the ISO – STEP international standards effort. Data model standards are developed both through the ISO organization and by industry - led efforts, using the same technology, specifically the *EXPRESS* data modelling language. EXPRESS is machine-readable and has multiple implementations, including a compact textfile format, SQL and object database implementations and XML implementations.

All are in use. The two main building product data models are the *Industry Foundation*

Classes (IFC) – for building planning, design, construction, management, and CIMsteel Integration Standard Version 2, (CIS/2) for structural steel engineering and fabrication. Both IFC and CIS/2 represent geometry, relations, processes and material, performance, fabrication and other properties, needed for design and production, using the EXPRESS language. Both are frequently extended, based on user needs.

Because EXPRESS supports applications with multiple redundant types of attributes and geometry, two applications can export or import different information for describing the same object. Efforts are being made to standardize the data required for particular workflow exchanges. In the US, the main effort is called the *National BIM Standards* (NBIMS) project. Interoperability imposes a new level of modelling rigor that firms are still learning to manage. Other formats for model viewing – 3D PDF and DWF – provide capabilities that resolve some types of interoperability problems.

While files support exchange between two applications, there is a growing need to coordinate data in multiple applications through a *building model repository*. Only in this way can the consistency, data and change management be realized for large projects. However, there are still some unresolved issues in the general use of building model repositories.

Data exchanges between two applications are typically carried out in one of the four main ways listed below:

1. Direct, proprietary links between specific BIM tools

2. Proprietary fi le exchange formats, primarily dealing with geometry

3. Public product data model exchange formats

4. XML - based exchange formats

Direct links provide an integrated connection between two applications, usually called from one or both application user interfaces. Direct links rely on middleware software interfacing capabilities such as ODBC or COM or proprietary interfaces, such as ArchiCad’s GDL or Bentley’s MDL. These are all programming level interfaces, relying on C, C__ or now C_ languages. The interfaces make portions of the application’s building model accessible for creation, export, modification or deletion.

A proprietary exchange file format is one developed by a commercial organization for interfacing with that company’s application. While a direct linking of applications is a runtime and binary interface, an exchange format is implemented as a fi le in a human readable text format. A well-known proprietary exchange format in the AEC area is DXF (Data eXchange Format) defined by Autodesk. Other proprietary exchange formats include SAT (defined by Spatial Technology, the implementer of the ACIS geometric modelling software kernel), STL for stereo - lithography and 3DS for 3D - Studio. Because each of these has their own purpose, they address functionally specific capabilities.

The public level exchange formats involve using an open - standard building model, of which the IFC (Industry Foundation Class) (IAI 2007), or CIS/2 (CIS/2 2007) for steel, are the principle options. Notice that the product model formats carry object and material properties and also relations between objects, in addition to geometry. These are essential for interfacing to analysis and construction management applications.

Software companies quite reasonably prefer to provide exchanges to specific companies using a direct link, because they can support them better, and it keeps customers from using competitor ' s applications. The functionality supported is determined by the two companies (or divisions within the same company).

However, because they have been developed, debugged and maintained by the two companies involved, they are typically robust for the versions of the software designed for, and the functionality intended. The resulting interface usually reflects a joint business agreement regarding marketing and sales.

The interfaces are maintained as long as their business relationship holds.

On the other hand, there is a natural desire to 'mix - and - match' applications to provide functionality beyond what can be offered by any single software company. The method of integration becomes critical for projects involving large teams, because gaining interoperability of different systems used by the team is easier than moving all team firms to a single platform. The public sector also wishes to avoid a proprietary solution that gives any one software platform a monopoly. Only IFC and CIS/2 (for steel) are public and internationally recognized standards today. Thus, the IFC data model is likely to become the international standard for data exchange and integration within the building construction industries. XML is eXtensible Markup Language, an extension to HTML, the base language of the Web. XML allows definition of the structure and meaning of some data of interest; that structure is called a *schema*. The different XML schemas support exchange of many types of data between applications. XML is especially good in exchanging small amounts of business data between two applications set up for such exchanges.

A summary of the most common exchange formats in the AEC area is listed in Fig13. Fig. 13 groups file exchange formats with regard to their main usage. These include 2D raster image formats for pixel - based images, 2D vector formats for line drawings, 3D surface and solid shape formats for 3D forms. 3D object - based formats are especially important for BIM uses and have been grouped according to their field of application. These include the ISO - STEP based formats that include 3D shape information along with connectivity relations and attributes, of which the IFC building data model is of highest importance. Also listed are various game formats, which support fixed geometry, lighting, textures along with actors, and dynamic, moving geometry, and geographical information system (GIS) public exchange formats for 3D terrain, land uses and infrastructure.

All methods of interoperability must deal with the issue of versions. When an application is updated with new capabilities, it may make the exchange mechanism faulty, if it is not maintained and versions of the standard are not well managed.

Image (raster) formats	
JPG, GIF, TIF, BMP, PIC, PNG, RAW, TGA, RLE	Raster formats vary in terms of compactness, number of possible colors per pixel, some compress with some data loss.
2D Vector formats	
DXF, DWG, AI, CGM, EMF, IGS, WMF, DGN	Vector formats vary regarding compactness, line widths and pattern control, color, layering and types of curves supported.
3D Surface and Shape formats	
3DS, WRL, STL, IGS, SAT, DXF, DWG, OBJ, DGN, PDF(3D), XGL, DWF, U3D, IPT, PTS	3D surface and shape formats vary according to the types of surfaces and edges represented, whether they represent surfaces and/or solids, any material properties of the shape (color, image bitmap, texture map) or viewpoint information.
3D Object Exchange formats	
STP, EXP, CIS/2	Product data model formats represent geometry according to the 2D or 3D types represented. They also carry object properties and relations between objects.
Game formats	
RWQ, X, GOF, FACT	Game file formats vary according to the types of surfaces, whether they carry hierarchical structure, types of material properties, texture and bump map parameters, animation and skinning.
GIS formats	
SHP, SHX, DBF, DEM, NED	Geographical information system formats
XML formats	
AecXML, Obix, AEX, bcXML, AGCxml	XML schemas developed for the exchange of building data. They vary according to the information exchanged and the workflows supported.

FIGURE 14. COMMON EXCHANGE FORMATS IN AEC APPLICATIONS [87]

3.3.3.1 Focus on IFC

The Industry Foundation Classes (IFC) was developed to create a large set of consistent data representations of building information for exchange between AEC software applications. It relies on the ISO - STEP EXPRESS language and concepts for its definition, with a few minor restrictions on the language. While most of the other ISO - STEP efforts focused on detailed software exchanges within specific engineering domains, it was thought that in the building industry this would lead to piecemeal results and a set of incompatible standards. Instead, IFC was designed as an extensible ‘framework model.’ That is, its initial developers intended it to provide broad general definitions of objects and data from which more detailed and task - specific models supporting particular workflow exchanges could be defined. In this regard, IFC has been designed to address all building information, over the whole building lifecycle, from feasibility and planning, through design (including analysis and simulation), construction, to occupancy and operation (Khemlani 2004).

IFCs consists of a library of object and property definitions that can be used to represent a building project and support use of that building information for particular use.

All objects in EXPRESS are called entities. The conceptual organization of IFC entities is diagrammed in Figure 14. At the bottom are twenty - six sets of base entities, defining the base reusable constructs, such as Geometry, Topology, Materials, Measurements, Actors, Roles, Presentations and Properties.

These are generic for all types of products and are largely consistent with ISO - STEP Resources, but with minor extensions.

The base entities are then composed to define commonly used objects in AEC, termed Shared Objects in IFC model. These include building elements, such as generic walls, floors, structural elements, building service elements, process elements, management elements, and generic features. Because IFC is defined as an extensible data model and is object - oriented, the base entities can be elaborated and specialized by subtyping * to make any number of sub - entities.

The top - level of the IFC data model are the domain - specific extensions. These deal with different specific entities needed for a particular use. Thus, there are Structural Elements and Structural Analysis extensions, Architectural, Electrical, HVAC, Building Control element extensions.

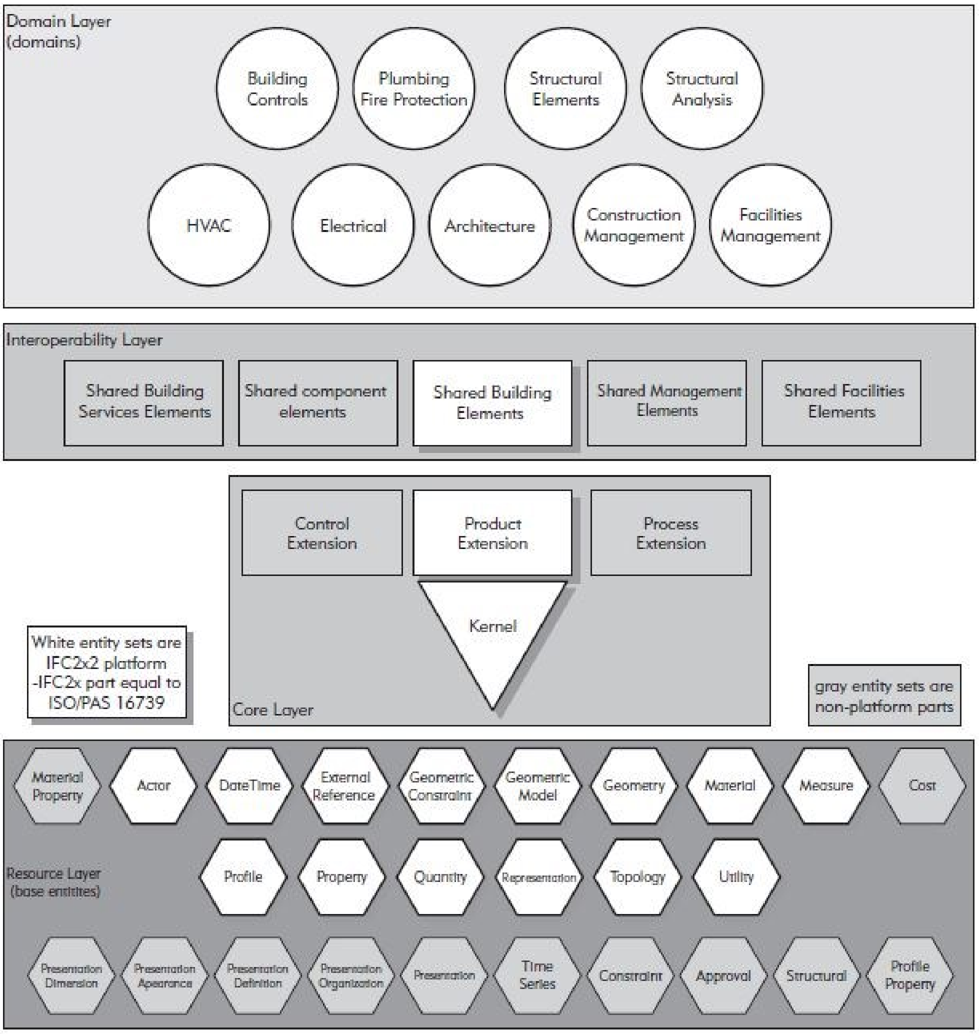


FIGURE 15. THE SYSTEM ARCHITECTURE OF IFC SUBSCHEMAS. [87]

Each of the geometric shapes in the system architecture diagram in Figure 15 identifies a set of EXPRESS language entities, enumerations, and types.

The architecture thus provides a type of indexing system into the IFC model, which is also defined in EXPRESS. The IFC model is quite large and still growing.

As of the current release 2x3, there are 383 Kernel - level entities, 150 shared entities in the middle level, and 114 domain - specific entities in the top level.

Given the IFC hierarchical object subtyping structure, the objects used in exchanges are nested within a deep sub - entity tree. For example, a wall entity has a trace down the tree:

IfcRoot → IfcObjectDefinition → IfcProduct → IfcElement → IfcBuildingElement →IfcWall

Each level of the tree introduces different attributes and relations to the wall entity. *IfcRoot* assigns a Global ID and other identifier information. *IfcObjectDefinition* optionally places the wall as part of a more aggregate assembly, and also identifies the components of the wall, if these are defined. *IfcProduct* defines the location of the wall and its shape. *IfcElement* carries the relationship of this element with others, such as wall bounding relationships, and also the spaces (including exterior space) that the wall separates. It also carries any openings within the wall and optionally their filling by doors or windows. Many of these attributes and relations are optional, allowing implementers to exclude some of the information from their export routines.

Products, including walls, may have multiple shape representations, depending upon their intended uses. Within the IFC, almost all objects are within a composition hierarchy defined by *IfcObjectDefinition;* that is, they are both part of a composition and have their own components. IFC also has a general purpose *IfcRelation,* which has different kinds of relations as subtypes, one of which is *IfcRelConnects,* which in turn has the subclass *IfcRelConnectswithRealizing* that is used to reference wall connections. This one example indicates the extensiveness of the IFC model. This type of approach is followed for all IFC modelled objects.

3.4 Virtual Reality for Engineering and Artificial Intelligence

As reported in [9], although video games have been available for almost thirty years, it was hard for non-professional programmer to create games for purposes. Fortunately, this has been changed recently since the editors used to modify the games have become sophisticated enough but conversely simple enough to be considered useful for different end-users [88]. Currently, these dedicated game editors, named Game Engine, have made possible to creation of games for non-professional, which allow them to easy insert architectural design elements into the video game, and then enables significant architectural visualization in game environment ([88], [89], [90], [91], [92], [93]).

Better still, these releases were not specifically for the benefit of architectural designers, but rather were to support people wanting to use the Game Engines to fulfil their research gaps such as spatial interaction management and building emergency management ([94], [95], [96]).

3.4.1 Architecture visualization

Several successful research studies that integrate with CAD/BIM and game have shown that Game Engine can serve as an enabler to improve architectural visualization and emergency management to a higher level. Specifically, on the one hand, BIM provides several options to control the output of the 3D geometry, which is a valid approach to provide multi-purpose output from its core model. On the other hand, Game Engines support importing meshes and 3D geometry in certain format from external software including BIM software to game environment. Therefore, it is feasible to propose a workflow to combine BIM and game when Game Engine supports whatever formats the BIM software outputs. With unique technologies such as physic engine and artificial intelligence, it is possible to extend functionality of current BIM software employing a Game Engine. With the advanced compatibility of technology, it is realistic to propose using game technology in professional design offices [97]. The following sub-sections introduce several developing methodologies utilizing different Game Engines to build a bridge between BIM and game to enhance architectural visualization.

Unity 3D: As one of the most famous Game Engine, Unity3D is characterized by its cross-platform system, available in free and non-free versions. Moreover, games can be exported as standalone applications for OSX and MS Windows, for consoles such as XBox and Wii, and for smartphones running iOS or Android. More importantly, it supports web applets for online use, which can decrease the size of a game and promote its spread. In this Game Engine, “Assets” are referenced to external files, such as scripts, textures and models. They are assembled into different game scenes or levels for different purposes with the integration of internal game objects. The imported assets is actually referenced instead of being fully embedded and they can be reloaded after some assets changes [98]. Figure 16 illustrates how this Game Engine works with some CAD/BIM software. The FBX format seems ideal to translate geometry and material information from BIM/CAD model into the Game Engine. However, in practice, when importing FBX format into Game Engine, it cannot automatically attach materials to the corresponding surface of objects.

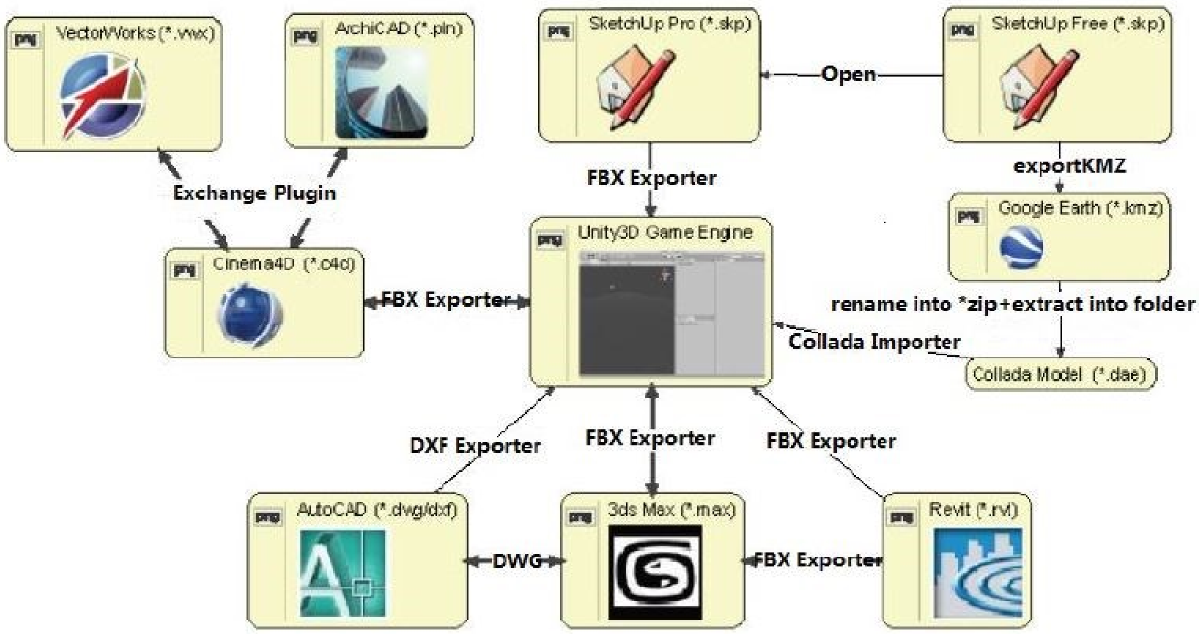


FIGURE 16. UNITY3D GAME ENGINE AND PREFERRED INTEGRATION WITH CAD/BIM SOFTWARE (BOEYKENS 2011)

In the future, when this Game Engine is combined with linking and filter of CAD/BIM assets (i.e. elements), a very flexible system can be created. It is possible to link one filtering version of the BIM model with lower resolution and less detail to the real-time game environment to save CPU usage of a computer, while at the same time hosting a higher-resolution version for photorealistic rendering in BIM environment [99]. XNA: The XNA Game Engine developed by Microsoft allows developers to develop games for both PC and Xbox360 video game consoles. Better still, the XNA and its related tools are free for everyone. Therefore, XNA Game Engine is regarded as a cost-saving but efficient tool to combine BIM to game.

There are two ways to integrate XNA workflow with CAD/BIM model to enhance architecture visualization: (1) XNA workflow based on FBX format; (2) XNA workflow based on Revit API.

3.4.2 Serious game for human behaviour training and research

As mentioned before, building emergency management traditionally employs emergency drills or experiments to explore human emergency behaviour with the aim to enhance building safety preplan and evacuation process. However, this method has research limitations with regard to human behaviour in fire, such as resource cost for emergency experiments and the risk of physical danger to participants [100].

Another limitation is that participants clearly know they are in a safe environment and do not feel stressed. Some tend to predict possible activities in established scenario according to relative data-collection instead of their instinct response to extraordinary environment. All of these limitations make research reliability of people's behaviours under fire emergency questionable. Then, inaccurate human behaviour research will subsequently influence the success of emergency management for fire. The emergency drill and experiment can only be held after the construction has been completed. It is too costly and time consuming to rectify the building layout if the defect of building design is found.

Fortunately, serious game generated by Game Engine can research and train human behaviours based on individual "human factors" during emergency situation [95]. Serious games can usually be expressed as (digital) games are not only used for mere entertainment but for other purposes such as education, simulation and analysis ([101], [102]). It seems "serious" and "game" are mutually exclusive. Specifically, "serious" plans to reflect the "purpose" of the game (i.e. why it was created) according to [103]. As for "game", "fun" component must come first. Without "fun", their use for various purposes is questioned [104]. Michael and Chen [103] argue that the main purpose of serious game to learn is of primary importance, and if possible, have fun doing it. More broadly speaking, education can be entertaining since the "fun" is only one kind of entertainment. There are a lot of elements that can contribute to the engagement of players. For examples, playing can promote the intense and passionate involvement, rules can generate a rigorous and scientific structure, and goals can motivate players to fulfil their potentials ([104], [105]). The difference between serious game and entertainment game can be concluded as following table [101]:

	Serious Game	Entertainment Game
Objective	Utilize the model and simulation to solve problems	Get rich experience through the game
Focus	Education, train and learn	Have a fun
Simulation	Take necessary and correct assumption to make sure the simulation is workable and realistic	Simplify the simulation process by some technologies (e.g. by random numbers, time compression, etc.)
Communication	Natural (i.e. non-perfect) communication	Perfect communication without delays and misunderstanding

FIGURE 17. DIFFERENCE BETWEEN SERIOUS GAMES AND ENTERTAINMENT GAMES [101]

Serious game has become a powerful tool to address the wide range of problems since its adoption in the field of science and up-to-minus modern technologies. For example, game technology (Game Engine), communication technologies (sensors, HMD (head mounted display)) and sciences (computer science, psychology and education) can all be utilized to research emergency human behaviour rather than pure entertainment use [106].

To mix the virtual and physical world, the five main human senses including hearing, seeing, tasting, smelling, touching should be considered. The immersive factor of virtual environment can also be enhanced by adding audio effects (e.g., crack noise, fire roaring, human shouting and crying) [91].

Indeed, the augmented reality and simulated environments provided by serious games allow participants to conduct experiments that are impossible to conduct in real world due to safety, cost, and time ([107], [108]). It is also consistently shown that serious game can promote learning ([109], [105]) stated that serious games can support the development of a number of skills, including analytical and spatial skills, strategic skills and insight, learning and recollection capabilities, psychomotor skills, visual selective attention, etc., and even violent games can alleviate frustration mood. However, it is difficult to draw any precise conclusion from studies on computer and video games because the conflicting outcomes of “serious” and “games”. Moreover, possible negative impacts may appear, including health issues (headaches, fatigue, mood swings, repetitive strain injuries, etc.), psychosocial issues (depression, increased gambling, etc.), and the effects of violent computer games (aggressive behaviour, negative personality development, etc.) [105].

Positive impacts of serious game on human behaviour research and enhancement have been reported by several researchers. Enochsson L et al. found a positive correlation between three-dimensional perception experience from computer gaming and better performance in endoscopic simulation by medical students ([110]). In the field of architecture and design, computer game can be utilized to develop students' confidence and abilities in space modelling and design innovation ([111], [112]). Guy et al. indicate that three-dimensional models hold a huge potential in enhancing town planning [113].

Experiments conducted by some software for attention training have shown that even the casual experience with computer games improve the attention behaviours of children [114].

Other potential benefits of games include improved self-monitoring, problem recognition and problem solving, decision making, better short-term and long-term memory, and increased social skills such as collaboration, negotiation, and shared decision-making ([115]; [105]; [116]). For example, playing on-line community game develops the ability to find information and solve the problem online [117]. Gamers develop their thinking strategies towards more analogical thinking rather than trial-and-error thinking [118].

The role-playing games have demonstrated its efficiency in corporate training by the mechanism of competitive scoring and difficult levels [119]. Squire and Jenkins ([120]) argue that games can be a powerful way of introducing new concepts and bind disparate period of history. In terms of relationship between gaming experience and driving behaviour, Backlund et al. ([121]) illustrate that a high experience in computer games can significantly improve the driving skills of traffic school students.

Another example is Baldaro et al. ([122]) who apply violent video game to evaluate short-term effects on physiological (arterial pressure and heart rate) and psychological (anxiety and aggressiveness) factors and reveal that there is no effect on hostility measures. Similarly, a survey by Durkin and Barber ([123]) showed that there is no evidence of violent game posing obvious effects on measures of aggressiveness. On the contrary, some experiments actually indicated reductions in aggression ([124]). Despite the above findings, there is still no conclusive answer to the question of evidence for benefits and potential consequences of playing game. However, Eck ([109]) pointed out the subsequent research direction: there is a need for practical guidance regarding how (when, with whom, and under what conditions) to integrate games and learning processes to maximize their learning potential and explain why these serious games are engaging and effective.

According to Wikipedia, main users of serious games are the military, government, medical professionals, school educators and corporation workers while the popular fields of its application lie in the global education and corporate training market. Advantages of military serious game include improving hand-eye coordination, improving ability to multitask, ability to work in a team using minimal communication, and willingness to take aggressive action, foreign languages and cultural training ([103]). In the future, application areas for the military field would integrate with up-to-the-minutes game technologies such as massively multiplayer online games (MMOGs) and virtual reality training.

Governmental games often focus on various tasks to deal with terrorist attacks, disease outbreaks, biohazards, health care policy issues, city planning, traffic control, firefighting, budget balancing, ethics training, and defensive driving ([120], [103]). The scenarios of such government game can easily be carried out repeatedly with changeable degree of severity according to different situation to compare the game experiment results. It also allows fire fighters, police, and medical personnel to perform tasks in virtual worlds rather than real experiments that are too dangerous, impossible, or too expensive to be carried out.

Healthcare games are one of most common serious game. There are a great number of serious games related to physical or mental health ([101]). Physical fitness game utilizes input devices like Wii controller and dance pad to promote physical exercise. Health/self-directed care game teaches the end users nutrition and health skills. Distraction therapy game helps patients decrease pain and anxiety before and during surgery. Recovery and rehabilitation game is beneficial for recovery of certain operation such as increasing motor ability of stoke patient. Training and simulation game can improve surgery performance. Game for diagnosis and treatment of mental illness can be used for diagnosing and treatment. Cognitive functioning game can develop memory and analytical/strategic skills. Control game with biofeedback equipment such as sensors that measure heart rate can train emotional and mental control of human being.

Although the benefits brought by education game is controversial ([116], [103]), the school educators can get the positive effects of education games in different field, which mainly include developing various human skills like strategic thinking, planning, communication, collaboration, group decision making, and negotiating skills ([125], [107]). To realize the full potential of games as education tools, some elements should be considered: resources (lack of education equipment, insufficient technical support, time consuming to be familiar with the game, etc.), how to merge the relevance of a game with statutory curricula, difficulty in persuading stakeholders to foresee the potential benefits of computer games, etc. ([116]). Similar to educators, workers in corporation can utilize serious game to train their various skills ([103]), including people skills (e.g. how to perform well within teamwork), job specific skill (e.g. how to use specific software and hardware to finish jobs efficiently), organization skills (e.g., how to manage human resources and time), communication skills (e.g. how to express ideas without aggravating others), strategy skills (e.g. how to set goals and achieve them).

Recently, serious computer games utilizing Game Engine are developing where "real" people can play virtually in their role in certain environment, which may provide the reliable data about human behaviour during emergency situation ([126]). The challenge is to combine virtual reality and computer game technology for a new kind of immersive, multiple-viewed, dynamic and interactive environment. Beyond that, the system of a building and its occupants can be regarded as a complex sociotechnical system: there are interactions between the building (technical aspects) and the human behaviour (social aspects) which influence each other. The technical aspects are easier to model and to simulate than the realistic behaviour of involved people because it is based on individual decisions in certain situations.

3.5 Internet Of Things - IoT

New technologies, even if not native for this purpose, constitute a great support in the acquisition of punctual and updated information.

For the purpose of acquiring information about the occupancy and the status of the several spaces, new monitoring technologies, belonging to the sector of IoT (Internet of Things) may have a great impact.

The internet of things, or IoT, is a system of interrelated computing devices, mechanical and digital machines, objects, animals or people that are provided with unique identifiers (UIDs) and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction. A thing in the internet of things can be a person with a heart monitor implant, a farm animal with a biochip transponder, an automobile that has built-in sensors to alert the driver when tire pressure is low or any other natural or man-made object that can be assigned an IP address and is able to transfer data over a network.

Increasingly, organizations in a variety of industries are using IoT to operate more efficiently, better understand customers to deliver enhanced customer service, improve decision-making and increase the value of the business.

History of IoT

Kevin Ashton, co-founder of the Auto-ID Centre at MIT, first mentioned the internet of things in a presentation he made to Procter & Gamble (P&G) in 1999. Wanting to bring radio frequency ID (RFID) to the attention of P&G's senior management, Ashton called his presentation "Internet of Things" to incorporate the cool new trend of 1999: the internet. MIT professor Neil Gershenfeld's book, When Things Start to Think, also appearing in 1999, did not use the exact term but provided a clear vision of where IoT was headed.

IoT has evolved from the convergence of wireless technologies, microelectromechanical systems (MEMS), micro services and the Internet. The convergence has helped tear down the silos between operational technologies (OT) and information technology (IT), enabling unstructured machine-generated data to be analysed for insights to drive improvements.

Although Ashton's was the first mention of the Internet of Things, the idea of connected devices has been around since the 1970s, under the monikers embedded Internet and pervasive computing.

The first Internet appliance, for example, was a Coke machine at Carnegie Mellon University in the early 1980s. Using the web, programmers could check the status of the machine and determine whether there would be a cold drink awaiting them, should they decide to make the trip to the machine.

IoT evolved from machine-to-machine (M2M) communication, i.e., machines connecting to each other via a network without human interaction. M2M refers to connecting a device to the cloud, managing it and collecting data.

Taking M2M to the next level, IoT is a sensor network of billions of smart devices that connect people, systems and other applications to collect and share data. As its foundation, M2M offers the connectivity that enables IoT.

The internet of things is also a natural extension of SCADA (supervisory control and data acquisition), a category of software application program for process control, the gathering of data in real time from remote locations to control equipment and conditions. SCADA systems include hardware and software components. The hardware gathers and feeds data into a computer that has SCADA software installed, where it is then processed and presented it in a timely manner. The evolution of SCADA is such that late-generation SCADA systems developed into first-generation IoT systems.

The concept of the IoT ecosystem, however, did not really come into its own until the middle of 2010 when, in part, the government of China said it would make IoT a strategic priority in its five-year plan.

How IoT works

An IoT ecosystem consists of web-enabled smart devices that use embedded processors, sensors and communication hardware to collect, send and act on data they acquire from their environments. IoT devices share the sensor data they collect by connecting to an IoT gateway or other edge device where data is either sent to the cloud to be analysed or analysed locally. Sometimes, these devices communicate with other related devices and act on the information they get from one another. The devices do most of the work without human intervention, although people can interact with the devices -- for instance, to set them up, give them instructions or access the data.

The connectivity, networking and communication protocols used with these web-enabled devices largely depend on the specific IoT applications deployed.

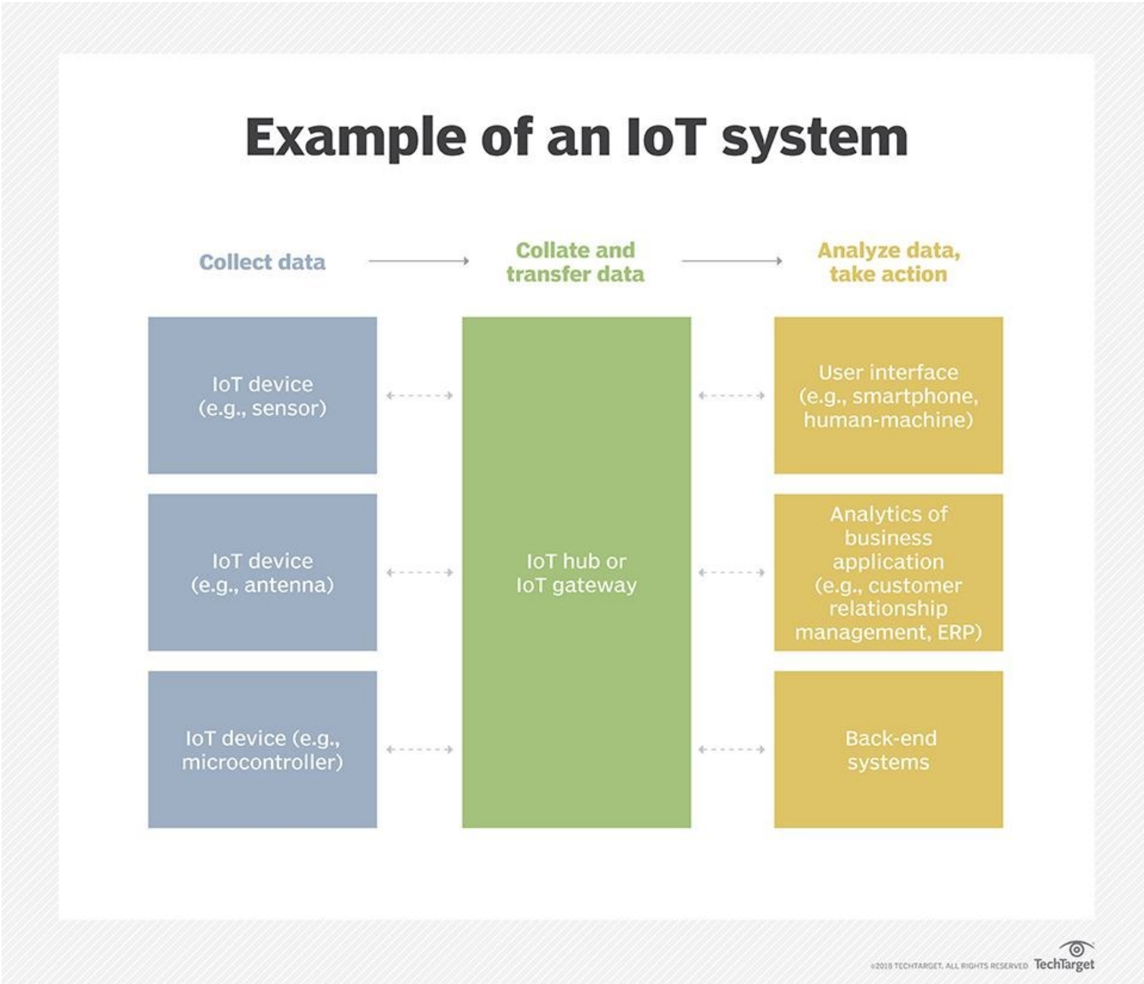


FIGURE 18. EXAMPLE OF IOT SYSTEM [127]

BENEFITS OF IOT

The internet of things offers a number of benefits to organizations, enabling them to:

- monitor their overall business processes;
- improve the customer experience;
- save time and money;

- enhance employee productivity;
- integrate and adapt business models;
- make better business decisions; and
- generate more revenue.

IoT encourages companies to rethink the ways they approach their businesses, industries and markets and gives them the tools to improve their business strategies.

CONSUMER AND ENTERPRISE IOT APPLICATIONS

There are numerous real-world applications of the internet of things, ranging from consumer IoT and enterprise IoT to manufacturing and industrial IoT (IIoT). IoT applications span numerous verticals, including automotive, telco, energy and more.

In the consumer segment, for example, smart homes that are equipped with smart thermostats, smart appliances and connected heating, lighting and electronic devices can be controlled remotely via computers, smartphones or other mobile devices.

Wearable devices with sensors and software can collect and analyse user data, sending messages to other technologies about the users with the aim of making users' lives easier and more comfortable. Wearable devices are also used for public safety -- for example, improving first responders' response times during emergencies by providing optimized routes to a location or by tracking construction workers' or firefighters' vital signs at life-threatening sites.

In healthcare, IoT offers many benefits, including the ability to monitor patients more closely to use the data that is generated and analyse it. Hospitals often use IoT systems to complete tasks such as inventory management, for both pharmaceuticals and medical instruments.

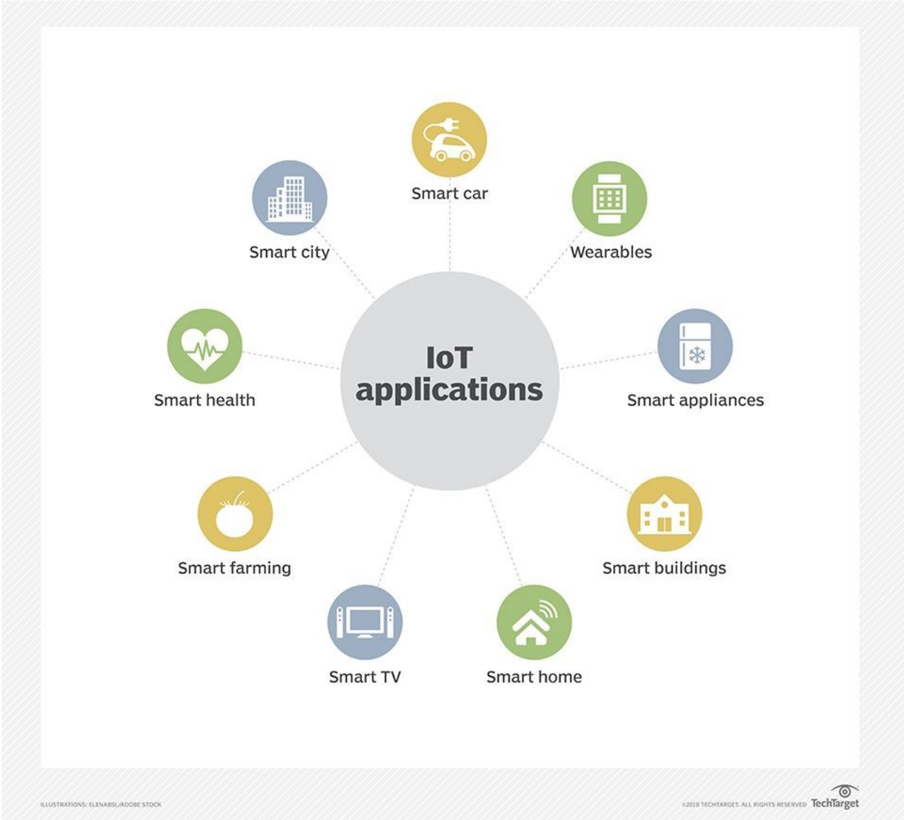


FIGURE 19. IOT APPLICATIONS [127]

Smart buildings can, for instance, reduce energy costs using sensors that detect how many occupants are in a room. The temperature can adjust automatically -- for example, turning the air conditioner on if sensors detect a conference room is full or turning the heat down if everyone in the office has gone home.

In agriculture, IoT-based smart farming systems can help monitor, for instance, light, temperature, humidity and soil moisture of crop fields using connected sensors. IoT is also instrumental in automating irrigation systems.

In a smart city, IoT sensors and deployments, such as smart streetlights and smart meters, can help alleviate traffic, conserve energy, monitor and address environmental concerns, and improve sanitation.

IoT SECURITY AND PRIVACY ISSUES

The internet of things connects billions of devices to the internet and involves the use of billions of data points, all of which need to be secured. Due to its expanded attack surface, IoT security and IoT privacy are cited as major concerns.

One of the most notorious recent IoT attacks was Mirai, a botnet that infiltrated domain name server provider Dyn and took down many websites for an extended period of time in one of the biggest distributed denial-of-service (DDoS) attacks ever seen. Attackers gained access to the network by exploiting poorly secured IoT devices.

Because IoT devices are closely connected, all a hacker has to do is exploit one vulnerability to manipulate all the data, rendering it unusable. In addition, manufacturers that don't update their devices regularly -- or at all -- leave them vulnerable to cybercriminals.

Additionally, connected devices often ask users to input their personal information, including names, ages, addresses, phone numbers and even social media accounts -- information that is invaluable to hackers.

However, hackers are not the only threat to the internet of things; privacy is another major concern for IoT users. For instance, companies that make and distribute consumer IoT devices could use those devices to obtain and sell users' personal data.

Beyond leaking personal data, IoT poses a risk to critical infrastructure, including electricity, transportation and financial services.

3.6 CONSIDERATIONS AND SUGGESTIONS

In this section we have reported the measures in which the aforementioned theories have inspired us in our research, as starting point of our study in the development of a novel helpful methodology for emergency management in case of unexpected events occurring. Brief considerations regarding the possibilities to exploit the aforementioned technologies in the building up of our developed system architecture are supplied.

In our research, we have found the holonic theory as the main milestone because of its potentialities of providing the actual hierarchical management approach with the required flexibility, while preserving robustness. We retain that enabling a more fluid decision process, the whole management system would benefit of a greater capability to adapt to the actual situation and react to rapidly evolving scenarios, like in our matter of study of unexpected events occurring in emergency situations. Moreover, we have found that the possibility of holons to be both autonomous to solve local criticalities and cooperative to achieve higher common objectives by forming temporary collaborative groups (namely the holarchies), would supply a great contributions to solve local criticalities in a time effective manner avoiding the slowing down bottom-up information and top-down decision flows.

Our reference architecture has been PROSA in the meaning of having different agents containing knowledge about the process and the product. In our case they correspond respectively to the emergency operations to be executed (how to find a way out of the building, extinguish fire, etc.) and to the objective of the emergency operations (make people evacuating, stop fire propagation, etc.). Furthermore, we have retained useful also the employment of delegates agents in search of information about the evolving scenario (a sort of "exploring ants") and about resources availability in order to estimate the feasibility of possible executable rescue actions (a sort of "intention ants").

Regarding Bayesian Networks, we have retained to demand to them the decision-making about different competing alternative plans, for their great capability to cope with uncertainties and produce valid estimations also in case of missing or incomplete data, as it may happen in circumstance like the one we have intended to deal with.

BIM models have been employed to represent the examined buildings and infrastructures for their characteristics of provider of comprehensive, coherent and non-redundant data about the managed spaces and for high level of interoperability with other software, they assure through the means of apposite interchange file formats.

Serious game engine developed in Virtual Reality Platforms such as Unity 3D, represent a powerful mean to reproduce the emergency environment importing building data from BIM models and other information from pervasive sensors distributed on site. Beyond their high interoperability with specific engineering software enabled by importing functional mock ups, it offers extremely realistic environment to simulate emergency scenarios and building occupants' behaviours by means of Artificial Intelligence.

Finally, IoT systems could be of extremely help during emergency management because of their easiness in the deployment of devices on site, reliability and robustness in case of failures of some sensors.

E.g. Thermal imagery cameras could give more precise information about the fire evolution, while punctual real-time location system devices might offer a constantly updated and precise information about the occupancy of the spaces, giving an overall picture of the evacuated spaces. In [10], the author focuses on the key role covered by the knowledge of the spaces where rescuers intervene: rescuers and not so rarely, the occupants mainly of public buildings have to face emergency inside spaces that result unknown to them. Real-time location systems, based on several technologies, from RFID tags for assets and people, Ultra Wide Band or magnetic beacons to detect people wearing specific badges to Ultra Wide Band radar able to detect people inside the monitored spaces, as well as infrared cameras, constitute an enormous support in the evacuation processes, making the actions focus only on the spaces where people are present and often stuck.

In the next chapter, the methodology developed by the means of the aforementioned described theories and technologies is fully reported, along with the carried out scientific developments.

4. METHODOLOGY

4.1 INTRODUCTION

This section is devoted to the presentation of the methodology developed by our research group in the attempt of supplying a response to the weaknesses emerged in the analysis of the traditional emergency management approach, through the proposal of a novel enhancing one. The chapter provides first an introduction aimed at addressing the main revealed issues, then the architectural principles and the consequent system architecture created do embody the methodology are presented and fully described. The application of the developed methodology to a specific case study is reported in the following chapter 5.

4.2 ADDRESSED ISSUES

The traditional approach to the emergency management is based on a rigid set of operations ruled by a hierarchical structure of the involved rescuers. Orders concerning the procedure are issued up down, on the basis of the information gathered on site by the lowest levels of the hierarchy, implying two kinds of criticalities:

1) The decision process is based upon obsolete data, which may not reflect the actual situation;
2) When orders are converted into actions, the scenario should be already modified, with the consequence that they are no more effective to solve the original problem.

Therefore, the decision process lacks the necessary flexibility to be proactive especially in rapidly evolving scenarios as emergencies.

The information flow is often not effective since the information transmission means can be seriously affected by damages or overload due to the huge requesters of use. The first consequence is the inhibition of communications among building occupants and rescuers that reflects the impossibility to update information on the real status of the evolving environment and to distribute evacuation instructions, which are demanded basically to static means such as emergency plans, often characterized by a not clear and effective understandability.

This section provides first a deep consideration of these aspects, then the novel approach that has been developed in order to provide a new methodology to face unforeseen events during emergency scenarios.

The first consideration lies in the impossibility of representing all the possible events that may occur during an emergency scenario. Actual emergency plans and measures are valid for general emergencies of each kind, on the basis of a common sense of risk acceptability, which is represented by the “norms”. The norms provide instructions to save building occupants and limit the damage to the building elements, they aim both at the planning phase of buildings and at the emergency management itself through rescue operations. The preplanning phase aims at guaranteeing sufficient stability to the building and escape routes correctly dimensioned to allow draining building occupants outside during an emergency. Specific devices and plants, like anti-fire alarms, smoke detectors, fire extinguishers, fireproof ladders, are then dimensioned and properly located inside the several spaces in order to handle with the emergency causes, such as fire. Rescue and panic management training are also often performed in order to exercise rescuers in the operations and make people aware of the proceeding measures in case of emergency.

Nevertheless, these typical measures, although necessary, have not always shown a good performance, especially when operations or the decision making process have been seriously affected by unexpected events or the scenarios have evolved in an unforeseen way.

The majority of the methods until now developed in the emergency management are knowledge-based; consequently, they strive to give a precise picture of the system status and of the building occupants’ behaviours, without taking into account any kind of unexpected events and factors that may affect the overall operations. The major risk of this approach is an over-simplification of two complex systems: the environment status evolution and the behavioural status of the building occupants. Both systems are indeed characterized by a great level of complexity, which cannot be reduced to a set of general cases that suit in every circumstance, including when disturbances affect the standard foreseen evolution of the system. Furthermore, the representation of all the possible events that may occur is not feasible since it would led to a combinatorial explosion, with the consequence of unacceptable times in the resolution of criticalities.

Based upon these observations, our research group has realized that a concrete improvement to the emergency management could be reached by a shift in the methodology applied, from an IF-THEN approach to a WHAT-IF one. Starting from the unfeasible representation of all the system status evolutions under unforeseen disturbances, the first consideration is that the system should be capable to acquire knowledge only when needed, namely in the current situation. The knowledge process has to be intended no longer *a priori;* rather it has to be triggered by the actions: the current situation, when in presence of unexpected and unforeseen events justifies the search for alternative solutions. Therefore, there is no longer the consideration of a pre-fixed scenario corresponding to an IF-THEN switch of actions, rather a WHAT-IF approach in the meaning that if an accident happens, the system must immediately react and respond looking for solutions that are alternative to the standard ones. In this kind of approach, knowledge is not considered as a-priori available from the initial data at our disposal, therefore small tests are conducted in order to assess the system's reaction to the unexpected events that may vary the initial conditions, making them obsolete and no more correspondent to the actual situation. The WHAT-IF method promotes the exploitation of several alternative solutions by the means of real-time small tests that provide several different reactions of the system that is forced to self-reorganization in response to the unforeseen events.

The selection among several "unconventional" measures to reach the objective of escaping from the place where the emergency occurs, must be based upon the most updated knowledge even if with partial data: in order to have a real-time effective reaction to the situation currently in place. This one must be learned only when needed through specific focused attempts that, by the means of real-time simulations, produce the "knowledge" required at the moment.

The system must be enough reactive to take actions also in case of missing of all the data concerning the whole environment.

Centralized decision processes reveal that the complete acquisition of all the data often is a too much time-consuming action, not rarely causing decision-making based upon obsolete data that do not reflect the evolved situation and are, therefore, not decisive to solve the current problems. In contrast to the actual approach, that provides a bottom-up flow of information and a top-down decision-making process, our proposal is to make the system more flexible, which means consequently more effective. Taking inspiration to the holonic theory (chapter 3.1), our system is conceived as reflecting the bio-mimesis. Like in the human body each organ contains its own knowledge and capability to work, even if the brain has a major control on them, our system proposes to respect the "brain" in the meaning of the emergency norms and instructions, while maintaining a certain degree of freedom in acquiring information and exploit them to fulfil local objectives.

More precisely, we share Koesteler's vision of holons as sub-entities endowed with a remarkable degree of autonomy or *self-government*. As the author deeply explains, the term holon may be applied to any stable sub whole in an organism, cognitive, or social hierarchy which displays rule-governed behaviours and/or structural gestalt constancy. Thus, biological holons are **self-regulating "open systems"** governed by a set of fixed rules, which account for the holon's coherence, stability, and its specific pattern of structure and function. This set of rules we may call the ***canon of the holon***. The canon determines the fixed, invariant aspect of the open system in its steady state; it defines its pattern and structure. In other types of hierarchies, the canon represents the codes of conduct of social holons (family, tribe, nation, etc.); it incorporates the "rules of the game" of instinctive rituals or acquired skills (behavioural holons); the rules of enunciation, grammar, and syntax in the language hierarchy; Piaget's schemes in cognitive hierarchies, and so on. The canon represents the constraints imposed on any rule-governed process or behaviours. However, these constraints do not exhaust the system's degrees of freedom; they leave room for more or less flexible strategies, guided by the contingencies in the holon's local environment. [13]

In our research, we have embraced this point of view on systems that even if ruled by a hierarchy, maintain a certain level of autonomy in their sub-wholes, considered as self-containing parts, on their own part of a higher system. We retain, according also to other research initiatives [71] that holonic systems for their characteristics of flexibility and relative autonomy could be the proper response to the limits of the actual emergency management approach, which reveals to be affected by a too rigid hierarchy and an over-simplification of the various scenarios that could occur in case of unexpected events. In this field, the emergency rules and norms represent the canons mentioned by Koestler: the norms reflect the highest level of social acceptability of risk and constitute the general laws and guidelines in case of emergency. A lower level of generality characterizes the prescriptions, which are based on general norms, though contain specific elements concerning the examined building: these are represented by the specific emergency plans and instruction of each building. They regard measures tailored for the building they refer to, taking into account specific portions and elements of it like anti-fire design, fire extinguishers, smoke detectors, escape routes for the implementation of set of rules to be applied in case of emergency, drawn up in accordance to the higher level constituted by the general norms.

Although these measures are designed according to deep studies of the emergency phenomena and their relative effects, these canons reveal to be not sufficiently flexible and adaptable to cope with the uncertainties affecting the continuously evolving scenarios typical of emergencies. Therefore, we propose a shift in the strictly prescriptive and *a-priori scenario based* of the traditional approach through the introduction of a certain level of autonomy and solving capability at the lowest level of the hierarchy. The acquisition of data in order to extract the most useful information, basically the knowledge creation process, in our vision, starts only when necessary, in order to prevent the information flow from slow down and inhibition due to a huge and, commonly not useful, amount of data to be processed and taken into account. The creation of knowledge is then justified by the actions that are triggered from the actual situation in order to face the present occurring of unforeseen events and in order to be effective, it should be able also to rely on missing or incomplete data, avoiding a too much time consuming process of acquiring data from the whole building.

Along with the knowledge creation process, also the decision making one must be sufficiently lean to result real-time effective. Both processes should be triggered *only when needed* in order to make the new approach more flexible, adaptable, robust and able to cope with unforeseen events.

On one side, the decision making process should be founded on the knowledge rapidly created concerning the updated situation and rely on the coherence and autonomy of the lowest levels of the hierarchy, on the other it should be as decentralized as possible, giving the possibility to solve local problems to the lowest levels of the hierarchy. When the solution of the problems at the lowest levels cannot be guaranteed by the single holons, another characteristic of these systems can be exploited: the cooperation among the single agents to reach a common goal.

The decentralization characteristic as well as the cooperation one, make the holonic systems extremely flexible and adaptable, giving them the capability to face uncertainty in a greatly agile manner: for these reasons, we believe that the holonic theory could operate the right shift in the actual emergency management approach that we propose and look for.

Our choice relies also on the success demonstrated in the application of the holonic theory to processes characterized by a high level of changes, uncertainty and unforeseen events like custom-based manufacturing and open-air engineering, as reported in chapter 3.

The properties of flexibility, robustness and adaptability to the contingent situation, which holonic systems are endowed with, make this theory largely applicable also in a not yet sufficiently explored sector like the one of the emergency management. In [71], the authors make several hypothesis about the application of the holonic systems to several fields, including emergency management, setting up *adaptive information infrastructure (AII)* for the purpose of assuring data transmission also in case of failures or damages to the main information infrastructure. This constitutes the first attempt in applying holonic system to the emergency management field, specifically focused on the adaptability and resilience of the information backbone. The same author, Ulieru, in [128] conducts a study about several levels of planning, operating a distinction among meta-planning and planning and more deeply in dynamic and static meta-planning when treating, more in general, complex systems that can be seen as NP-hard problems. The time required to solve NP-hard problems is not acceptable for the requirement of fast response in case of emergency. Therefore, Ulieru et al. propose a more effective planning activity, which is influenced by a more abstract layer of meta-planning. While planning aims for output goals, a more abstract layer, the meta-planning, aims at the system goals, directing the planning activities when several alternatives concur. The meta-planning could be static or dynamic: the static meta-planning selects a solution among a set of alternative plans already generated, on the contrary, dynamic meta-planning looks more deeply for alternative plans implementing also further decompositions of the problems, searching the solution that best fits to the system goals.

Our proposal starts from this approach and further develops this method, especially focusing on how to enhance the actual emergency management approach, lending the lacking flexibility and adaptability to cope with uncertainties, by the use of holonic systems.

Another important scientific contribution is represented by the concept of using general data in order to arrange rescue operations in unconventional manners. The resilience and real-time effectiveness of the system is reached by the capability of the system to react to obstacles in the normal process flow and find alternative solutions that are not usually provided by normal emergency plans also by exploiting resources that are not devoted to this purpose: from finding alternative ways out, to use unconventional means.

4.3 Architectural principles

The observations of the limits of the actual emergency management approach along with the analysis of current studies, as described above, have led us to elaborate a system architecture based on the following architectural principles:

- **Real-time** effectiveness: it must regard both the information flow and the decision making process. Since the system is continuously evolving, especially in complex scenarios like emergencies, it is not feasible to represent all the changing status it assumes, in order to provide the proper solution to the occurring situations. Moreover, the response of the system must be sufficiently reactive in order to result effective to face the situations that are in place.
- **Resilience:** the system must be reactive and adaptive to the new possible configurations that may occur, without compromising his primary function of managing the emergency scenario. Failure, interruptions, damages to the standard communication backbone systems as well as injuries or obstructions to the usual evacuation means must not impede the main objective of keeping people safe during emergencies.
- **Proactive and unconventional solving:** on the basis of the information gathered in a real-time manner, in order to be sufficiently resilient, the system must be capable to extract the information useful to reach its objectives also by general data, as well as to provide escape solutions with the employment of unconventional means.

The outstanding innovation of the developed methodology lies indeed in the capability of the overall architecture to make use of unconventional resources for the fulfilment of its general scope of saving building occupants.

Our reference architecture is inspired to PROSA and D-Mas system for open-engineering as presented in [84]. In this work, Valckenaers et al. Apply PROSA architecture [79] along with a Delegate Multi-Agent System (defined as D-MAS) to propose an online planning method versus an offline and *a priori* one, in a field full of uncertainties and accidents like the one of the open air engineering.

The basic holons, as in other works of the authors are:

3) Resource holon: entity characterized by its utility quantity and availability in a processing environment
4) Product holon: entity containing technical knowledge and quality requirements of a process
5) Order holon: entity corresponding to the process to be performed in terms of time of execution.

The order agent send delegate agents, namely:

6) Exploring ant agents: in search of data concerning the actual situation. They report information about the most updated status of the system
7) Intention ant agents: sent in search of resources to be exploited. The output of their search regards the presence and the availability of the discovered resources.

We retain that a similar approach could be exploited also in the exploration of the current status during emergencies and in the search of the available resources to fulfil local goals.

Moreover, we have introduced another element, which make distinction among the resources: not only we consider their availability at the moment, but also the time they take to be employed in a decisive manner. Overcoming the PROSA and D-Mas approach, we have introduced the concept of searching information and looking for resources *only when needed*: namely, when an unexpected event occurs affecting the standard rescue operations. Furthermore, considering that in this case we are dealing with a very sensitive argument like the emergency management, whose main goal consists of assuring building safety during natural or artificial disasters; the ***time*** in which the resources potentially found by the D-Mas, are available and solve the problem they are employed for, becomes of extremely importance. By the mean of this consideration, we have introduced the declination or real-time effectiveness in the sense of the acceptability in the execution of problem solving actions.

Our methodology therefore supplies a system characterized by a high level of flexibility and resilience by the means of a holonic system-based architecture, which employs both basic holons and delegate agents as generally expressed in [84]. The selection of the most feasible and effective actions to take is faced via a dynamic meta-planning as intended in [128].

This architecture is enhanced and reinforced by introducing the concepts of real-time effectiveness assured by a WHAT-IF approach aimed at creating knowledge and acting only when needed: this led to the other scientific contribution of our research, consisting in the exploitation of general data for the specific purpose required at the moment.

We have then outlined a sequence of phases that could be applied in case of emergencies, which make our architectural framework tangible and executable:

1) The elaboration of "General meta-plans": this represents the abstraction of the overall objective of the management system: namely the rescue of building occupants. It refers to general set of actions that could to be taken in case of emergency, independently from the specific type of building. The input of this phase is the presence of an emergency event, while the main output is a series of high-level objectives to be reached (evacuation through escape routes, fire extinction). The output is embodied by the order holon represent the processes to be executed in an acceptable timeframe.
2) The second phase is ruled by a probabilistic gambler, which receives data concerning the current situation during the emergency event and provides the most effective escape solution on the basis of the conditional probabilities of the evaluated aspects (namely the availability of the escape resources along with the feasibility of the considered emergencies measures). The input information about the status of the specific building and its portions involved in the emergency is supplied by the delegate exploring agents that are sent in search of data about the current situation. They may be represented by humans looking for what has happened as well as by distributed devices that give information about smoke and fire detection, temperature, spaces occupancy and density and so on. Their report of information lays the basis for the main output of this phase, consisting in a series of "medium level plans" to be taken at lower levels.
3) The feasibility of the execution of the single small actions that together build a low-level plan is investigated. Assigning different targets to the single delegate agents sent in search for the availability of the different resources, several methods are implemented and tested. The effectiveness of the single low-level plans constitutes the basis of the next final step.

4) The final solution is generated by the combination of the several single actions that have been declared as feasible by the previous phase in order to find medium executable emergency plans that allow to reach the objective in a time-effective manner. This phase has been implemented through an “ant-colony” approach. [129] By using an “ant-colony” approach, the agents are designated to test a series of possibilities in order to test each phase of the medium level plan. The results of this phase lies in the effectiveness and time execution of these single actions.

Via the execution of these phases in the predisposed virtual environment, it is possible to investigate and find unconventional means to execute escape operations, in case unexpected events occur in obstruction to the normal rescue actions, as provided by general evacuation plans.

The set-up of the above-described architecture in a virtual environment is described as follows and more specifically in chapter 5, reporting the case study.

4.4 System Architecture

The implementation of the described architecture has been envisioned in the following schema:

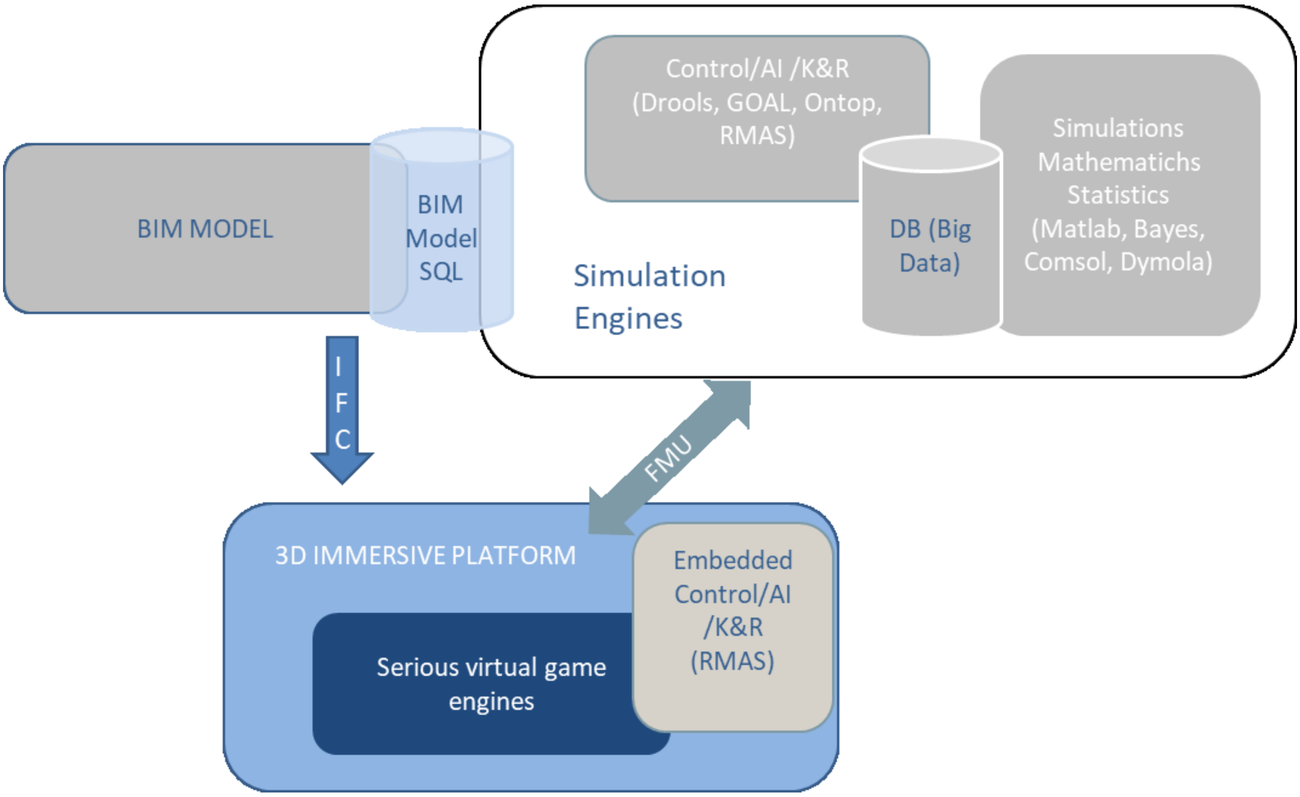


FIGURE 20. SYSTEM ARCHITECTURE [130]

Each component of the conceived architecture and the relative properties are going to be described as follows.

A. BIM models

A milestone of our research is the capability of extracting information from general data, for the specific purpose required *at the moment*. For this reason, BIM models have been selected as the proper and most suitable provider of topological information about the concerned buildings. The possibility of the models to be coherently updated during the whole lifecycle, selects the BIM models as the proper tools for the purpose of having a deeper knowledge of the spaces examined, that goes further beyond the static and poor information usually contained in emergency plans.

Furthermore, BIM can play a significant role in providing real-time and accurate building information under an emergent situation due to its comprehensive and standardized data format and integrated process.

The interoperability of BIM models with other software confirms their key role in our architecture: by utilizing data essentially produced to constitute a repository of the building status during its lifecycle, it is possible to gather information that are further exploited for our purposes. In our methodology, BIM is proposed not only as a comprehensive provider of the main building properties, but is subject to a proper ***semantic enhancement***: some building elements can be exploited in an "unusual way" respect to their main purpose and become evacuation means in an unconventional ways.

For engagement, if the usual escape routes are obstructed by smoke, fire, building elements collapse or other kind of accidents, internal doors that link spaces among each other, can represent the only way out from the spaces where the emergency has occurred. Therefore, common internal doors, not conceived as emergency ones may constitute the unique means to assure the escape.

In order to implement the interchange of data contained in the BIM model, a specific tool has been developed, defined as "IFC loader". This component allows the integration of BIM data through the import of IFC file into the chosen serious virtual game engine.

The Industry Foundation Classes (IFC) file format is maintained by buildingSMART®. IFC provides an interoperability solution between different software applications. The format establishes international standards to import and export building objects and their properties. IFC improves communication, productivity, delivery time, and quality throughout the life cycle of a building. It reduces the loss of information during transmission from one application to another, with established standards for common objects in the building industry. [131]

The import component allows preserving all the information about BIM objects and their properties, updating the information contained in the virtual engine if the version of the imported IFC file has been modified. This guarantees a continuously update of the building information during its lifecycle.

B. Simulation engines

Simulation engines are employed with two main purposes:

8) The simulation of data about the evolving status of the monitored environment and the occupancy level of the examined spaces as acquired by the IoT sensors that may be deployed on site.
9) The implementation of the probabilistic selector of the most feasible medium level plan to apply among different plausible ones.

As stated before, a fluid information flow among all the actors involved in the scenario, the building occupants and the rescuers must be assured also in case of failure or damage to the standard communication backbone. The flow of information must be **updated regarding the current situation**, in order to make decisions that are effective in the actual scenario. Therefore, the information must be fed from several means, able to assure a continuity in the data transmission.

New technologies, even if not native for this purpose, constitute a great support in the acquisition of punctual and updated information.

For the purpose of acquiring information about the occupancy and the status of the several spaces, new monitoring technologies, belonging to the sector of IoT (Internet Of Things) may have a great impact. Thermal imagery cameras could give more precise information about the fire evolution, while punctual real-time location system devices might offer a constantly updated and precise information about the occupancy of the spaces, giving an overall picture of the evacuated spaces. In [10], the author focuses on the key role covered by the knowledge of the spaces where rescuers intervene: rescuers and not so rarely, the occupants mainly of public buildings have to face emergency inside spaces that result unknown to them. Real-time location systems, based on several technologies, from RFID tags for assets and people, Ultra Wide Band or magnetic beacons to detect people wearing specific badges to Ultra Wide Band radar able to detect people inside the monitored spaces, as well as infrared cameras, constitute an enormous support in the evacuation processes, making the actions focus only on the spaces where people are present and often stuck.

Simulations engines expressly developed in Matlab simulate the input of this kind of sensors, in order to test their applicability in our architecture. They are specifically employed to simulate the presence and the density of building occupants inside the buildings, representing the delegate exploring agents, whose purpose is to give a feedback about the actual status of the scenario.

The second purpose of simulation engine is realized through the employment of a probabilistic method, the Bayesian Network, in order to implement a “Bayesian gambler”, able to discern the most suitable medium level plan among several ones on the basis on the probabilistic inference.

This step provides medium level rescue plans that could be generated and are independent from the specific building. These represent general solutions that could be applied after the evaluation of several resources availability. The assessment of the feasibility of the medium level plans leads to the definition of lower level plans that have to be tested in order to be executed. The most promising solution is selected as the one with most probabilities of “success”: in our vision, this corresponds to the solution characterized by the highest level of feasibility, in terms of availability of resources to exploit in the execution of the single actions and time effectiveness of the series of actions involved.

Delegate agents in this case supply their feedback in the meaning of tested actions inside the virtual environment accompanied by information about feasibility and time of execution.

Feeding the network with data about the probability of success of the lower plans, by supplying information about resources’ availability, the single actions’ feasibility and relative time, it is possible to make probabilistic inference to select the most promising lower plan to be executed.

C. Serious game virtual engines

A virtual reality game engine has been selected as the proper collector of heterogeneous data to be combined together in order to extract information to be employed for the rescue aim during an emergency scenario. In this engine, the holons are triggered and simulated in order to produce the required knowledge.

This environment allows integrating data deriving from different sources and of different types, topological data regarding the built environment in the most updated version and data gathered by sensors deployed on site, useful to update the evolving states of the environment during the emergency. Information regarding the detection of the occupancy of the spaces and the evolving of the emergency, namely the spreading of smoke in the building during a fire emergency, are integrated along with geometrical representation in the building model and continuously updated. In the same environment, it has been possible to introduce elements of Artificial Intelligence by programming virtual agents, namely the “holons”, in order to react to the unforeseen events in an effective manner, by supplying real-time information about the environment and employing unconventional resources in order to achieve the objective of escaping from the building during the emergency. Cooperation among agents allows holons to negotiate for a wider objective in order to achieve their goals with mutual support.

BIM models have been employed as provider of information concerning topology and materials of the examined spaces, since they supply comprehensive, standardized data format along with integrated process.

In the proposed work, the environment built with the integration of BIM models and Game Engine has represented the test bed for the holonic theory applied to the emergency management. By simulating a fire scenario, agents have been modelled in order to react to casual events in a resilient way, exploring alternative solutions to the standard ones, in case these are not executable.

In our research implementation, we have selected Unity 3D as the proper virtual engine tool to simulate and assess the search of resources availability as well as the feasibility of the single alternative rescue operations. The link between BIM and Unity 3D has been realized through the “IFC loader” import tool as defined at point A. The virtual environment built in Unity 3D integrated with Revit, has constituted the 3D immersive platform, where several simulations have been conducted about agents’ behaviours in emergency management. The possibility to represent the building of interest as a 3d model containing all the relevant information.

This 3D immersive platform has allowed simulating agents’ behaviours in emergency situations in a dynamic and effective way. Pathfinding algorithm have been implemented in order to test

CHAPTER 5

Case Study

5. CASE STUDY

In order to implement and test our architecture, our research group has identified as a test bed a mixed-use building: “Eustachio” pole, located in Ancona (IT). The building belongs to a major complex of edifices occupied by the Faculty of Medicine of Università Politecnica delle Marche, Ancona. This eight storeys-building present a quite regular shape with two major blocks on the north and south side, containing spaces devoted to heterogeneous scopes: classrooms, scientific laboratories, administrative offices for students, a library, books storage rooms, services. The two main blocks are connected by the only two stairwells of the building, which present a separate reinforced concrete envelope that makes these parts separated from the block for seismic reasons. Interior spaces present some spaces characterized by different height levels (mainly the biggest classrooms) with specific interconnecting stairs, at ground and first level. The majority of plants is located in the basement: the thermal and hydraulic stations, the electrical generator, the medium-voltage substation, the water and natural gas shut-off valves and the technological plants; while at the eighth level, the seventh above ground, are located a voltage transformer and two boilers.

We have chosen this edifice for our test bed for its characteristic of public building with several uses that may involve variable flow of different people inside it: from frequent building users like professors, researchers, students, administrative and facility personnel to random visitors that could attend scientific conferences. The mixed use of the building constitutes an interesting aspect since the building occupants are different as well: characterized by several age ranges and, more specifically, owning a different level of knowledge of the building. Finally, the presence of inflammable substances in several laboratories, and the great interest in fire emergency, have led us to simulate the fire scenario in this building, since this is one of the most common and disruptive emergency situation, often affected by unexpected events and mistakes in the management of the evacuation process (see ref. to Grenfell Tower fire in chapter 1).

Therefore, the first step has regarded the deep analysis of the actual fire contingency plan, pointing out all the limits that characterize it and are typical of the actual emergency management approach, as described in the previous chapter. Following are described the implementation of our methodology to the specific case study, accompanied to a customization of our system architecture. Conducted tests and relative results are discussed in order to draw conclusions about the system architecture performance.

5.1 Assessment of the current fire contingency plan

Eustachio building is endowed with a specific fire contingency plan, drawn up and updated in several phases, among 2008 and 2013, in accordance with specific Italian laws: the Rector's Decree n.346/2013.

The main normative references are the Legislative Decree n.81/2008, namely the consolidated text of laws concerning Safety in Work Spaces, and the Ministerial Decree n. 10/1998, concerning "General criteria of fire safety and emergency management in work spaces", still in effect even if under review.

As stated in the first chapter of the plan, it consists in a series of technical measures with the following purposes:

1) Foresee or limit damages to building occupants and elements;
2) Coordinate the personnel's interventions in order to precisely define the behaviours to adopt to save their own integrity and limit damages to the structures;
3) Supply necessary references and information in order to activate the response at different levels on the basis of the several types of emergencies;
4) Coordinate the interventions of the Emergency Crew in order to supply an immediate and effective answer at various grades of emergency;
5) Supply assistance to disabled people in case of emergency.

Consequently, the principal terms are defined to depict and clarify the main concepts pertinent emergency causes and relative management.

After these sections, an analysis of the possible risk causes is conducted, in order to identify the possible trigger of danger. Inflammable materials and dangerous activities for fire triggering, especially among the ones carried out in the scientific laboratories, are detected and signalled.

The people flow in the building is highly variable and estimated between 100 and 2.320 individuals, with several roles and different purposes in the building utilization, therefore with different levels of knowledge and awareness of the several spaces.

Fireproof stairwells are identified in a half of the entire quantity provided, while not all the elevators are designed for fire protection: therefore, the only vertical connection to the outside are the four fireproof stairwells, highlighted in the picture below.

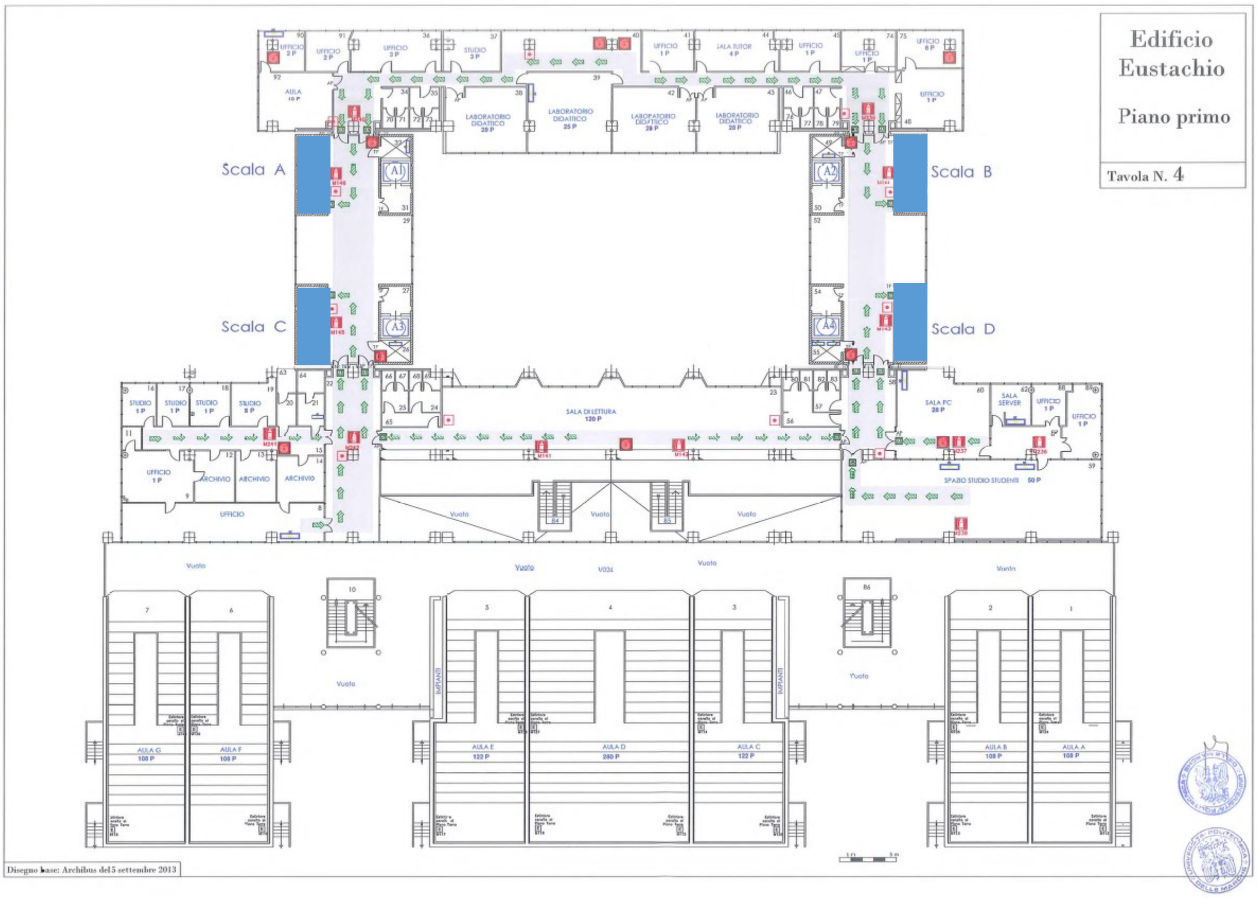


FIGURE 21. EMERGENCY PLAN – GROUNDFLOOR [132]

All the shafts are partitioned. The anti-fire station is located in the reception at ground level. Several anti-fire devices and detectors are distributed in the building,:

1) In the most fire-sensitive areas, automatic smoke and gas detectors are present, referring to the anti-fire central station;
2) In those areas and in the rest of the building are distributed fire alarms that can be manually activated and refer to the anti-fire central station as well;
3) Portable fire extinguishers and fire hydrant are located in visible places, along the escape routes towards the exits;

4) It is present a proper fire hydraulic network constituted by three water storage reservoirs in the basement.

Three types of emergencies are identified:

1) Emergency controllable with people on site detecting it
2) Emergency controllable with the interventions of the Internal Rescue Parties
3) Emergency that implies necessarily the operations of both the Internal Rescue Parties and the External Rescue Bodies.

Another distinction characterizes emergencies happening within or outside working hours. The workflow of the operations to be executed first during or outside working hours and then in case 2 and 3 are represented according to BPMN 2.0 standard [133] and deeply analysed, in order to make emerge all the criticalities affecting their flexibility and robustness on the basis of the observations presented and explained in the previous chapters.

The utilized notation is synthetized in the following legend:

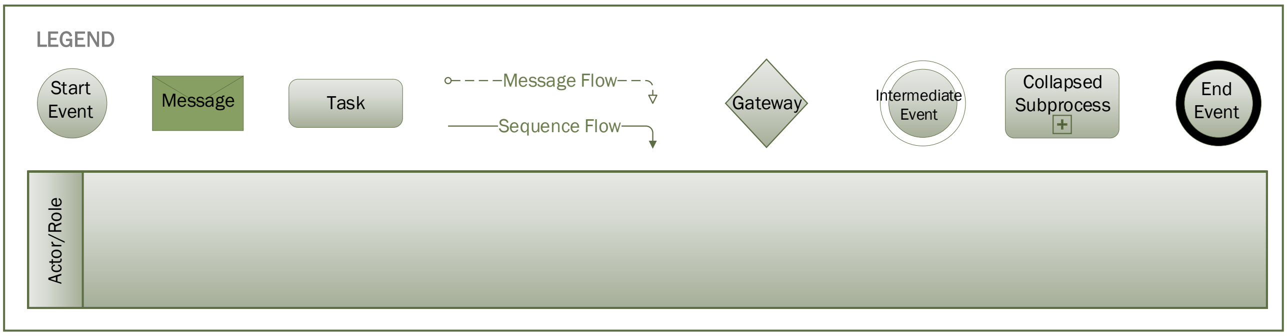


FIGURE 22. LEGEND OF SYMBOLS EMPLOYED IN THE WORKFLOW REPRESENTATION (BPMN 2.0 STANDARD)

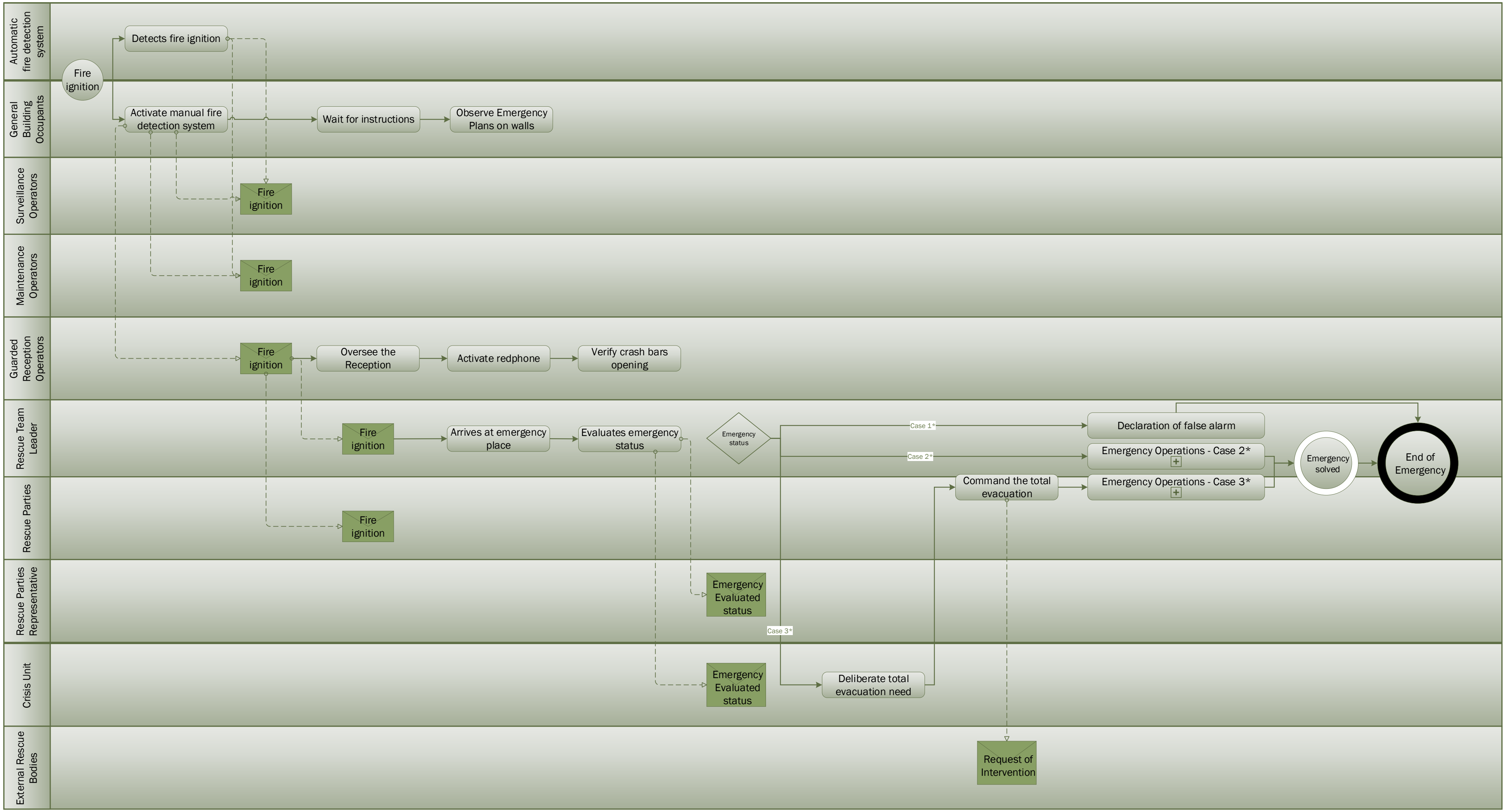


FIGURE 23. EMERGENCY MANAGEMENT WORKFLOW DURING WORKING HOURS

As depicted in the above workflow, the operations are guided by a rigid workflow, subject to a strong hierarchy. The data gathering process appears poor and relying only on human senses of people arrived on site, except from the spaces where automatic fire detectors are placed, namely, where there is a major risk of fire ignition.

Soon after the fire detection, the building occupants have to observe the general emergency plan hang on the walls of rooms and corridors, in accordance to the most common laws, and are obliged to wait for instructions by the rescue team. It means that the building occupants, according to the norm, are not allowed to intervene neither to evacuate until they receive a formalized instruction by the rescue team. This implies a certain waste of time while the phenomenon is increasing.

Then, the Guarded Reception Operators must notify the event to the Rescue Team, guided by the Rescue Team Leader, who has in charge a visual inspection of the site where the emergency has started in order to define the gravity level of the situation. The Rescue Team Leader is the only actor in the workflow allowed to visually analyse the situation and deliberate about the emergency status, i.e. the data acquisition and elaboration along with the consequent extraction of the information to define the current status of the emergency is centralized. If the situation is deemed seriously critical in the sense it cannot be resolved with the only interventions of the internal Rescue Parties, then data about the observed status must be referred to the Crisis Unit which has in charge to deliberate the total evacuation of the building (case 3). The command is then received by the Rescue Team Leader and communicated to the Emergency Representative as well as to the building occupants. All the activities are coordinated in a hierarchical way as depicted in Fig.24.

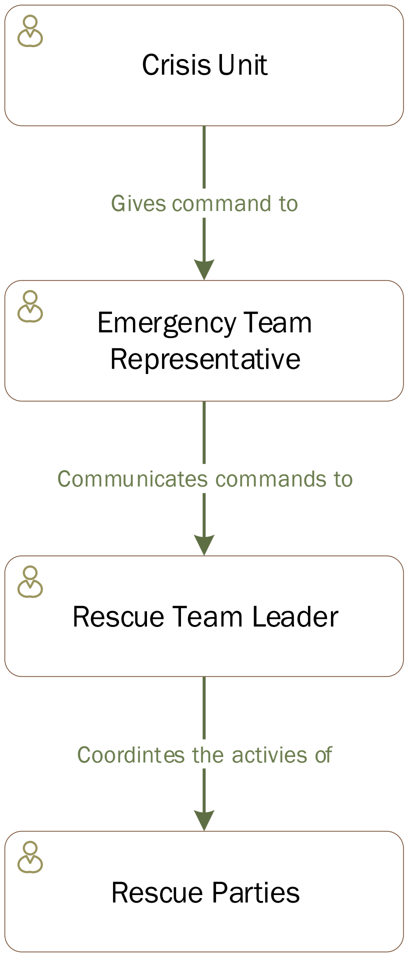


FIGURE 24. VISUALIZATION OF THE HIERARCHICAL WORKFLOW IN CASE 3

The centralization and the executive process produce generally a great slowdown in the workflow. First, the Rescue Team Leader must be always available and capable to reach the emergency place, then he has to verify personally the event acquiring information by directly going on site, with all the deriving risks and the consequence of a time consuming activity to search for all the relevant data in order to be able to make decisions. Finally, the centralized decision process could be seriously affected by a lack of information due to inaccessible data at the moment, that do not give a proper overview of the situation (e.g. smoke propagation, people present and stuck in some spaces).

Upon the decision regarding the emergency gravity level, depend the three possible sub-processes corresponding to cases 1, 2, 3.

An evenly more critical aspect is the total absence of unexpected consideration and of the need of a constant updating information flow. The data gathering about the event propagation, the distribution of the building occupants in the several spaces and any failures or damages to the structure play a key role in giving an effective picture of the current situation, in order to take then appropriate countermeasures. Nevertheless, these aspects are disregarded by the actual normative approach, since the emergency evaluation is totally depending on the visual inspection of the actors in charge (namely the Rescue Team Leader or some of his/her delegates), without considering the amount of relevant data that are therefore not taken into account. On the contrary, a too deep exploration of the building during the emergency could increase the occurring of incidents to the demanded actors, while would imply an ineffective time consuming activity. In conclusion, the countermeasures to take in case of unexpected events are neither mentioned.

On the basis of the analysed aspects, we can therefore notice that the overall system appears affected by a lack of flexibility and responsiveness to changing situations. In fact, on the one hand, the information flow relies on a restricted and not constantly updated amount of data; on the other hand, the system has a precise hierarchical structure where no space is provided for the management of unforeseen events.

The same consideration are valid for the emergency management workflow outside the working hours, although it is characterized by a minor set of actions, since the risk of injuries to the building occupants is strictly reduced by a low presence of people inside the building in not working hours, as illustrated in the following figure.

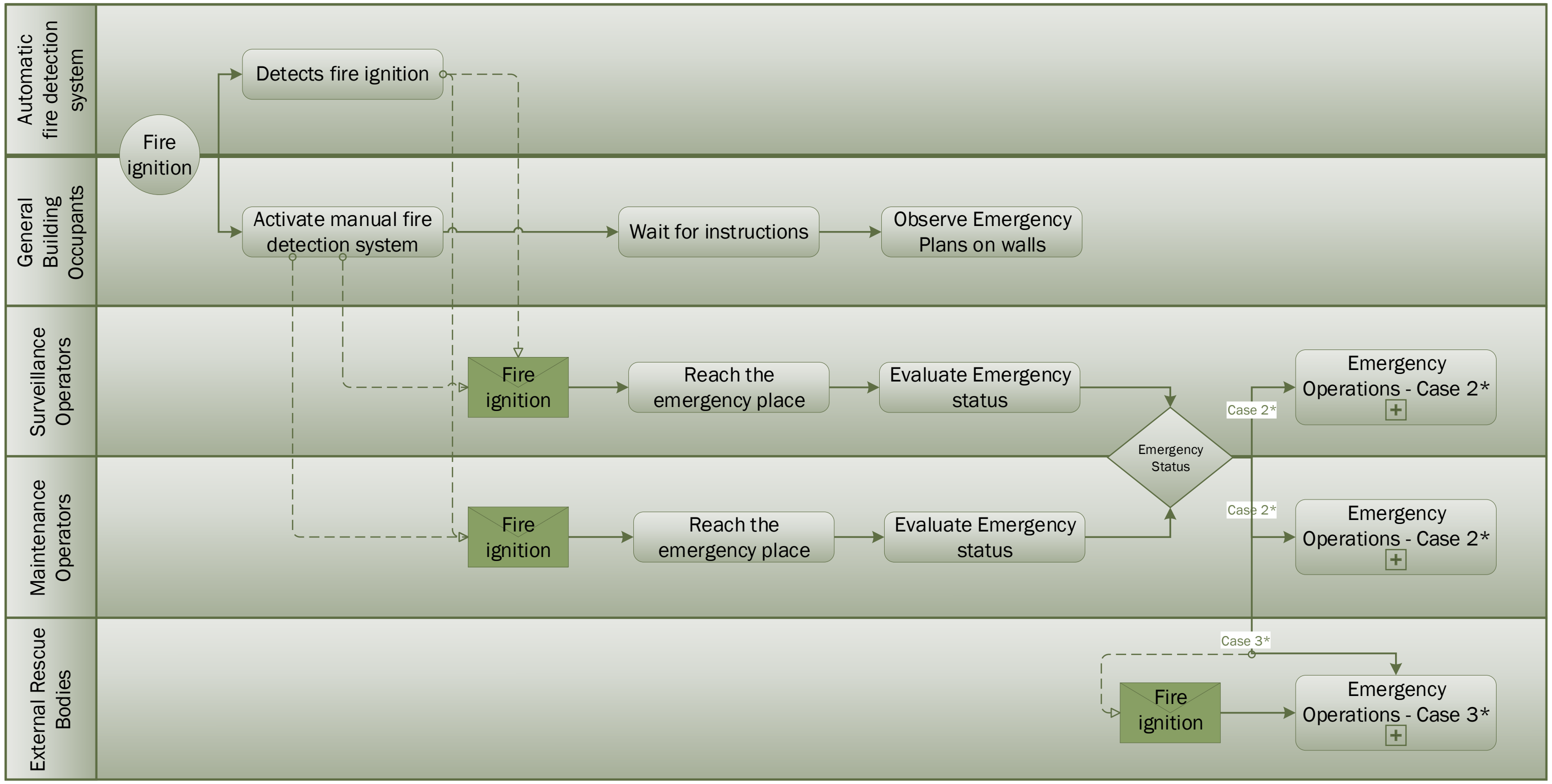


FIGURE 25. EMERGENCY MANAGEMENT WORKFLOW DURING WORKING HOURS

This workflow appears leaner since it involves a tight number of actors; the operators dedicated to maintenance and surveillance. They are demanded to all the operations from the emergency detection, the status evaluation, the fire extinction with internal means in case of a manageable incident and the alerting of External Rescue Bodies (namely the Fire Department) in case of an emergency that need the external intervention. Although this scenario could involve a minor number of building occupants, it has not to be underestimated, due to the damages that could be caused both to the people present in the building and to the structure. The reduced presence of people along with an irregular distribution of the automatic fire detectors inside the building could imply a not clear and immediate perception of the fire ignition, with the consequence of a too tardive awareness of the phenomenon and the consequent reparative operations.

As the previous one, also in this case, it can be noticed how scarce and ineffective could result the processes of detection of phenomena → awareness of the situation → evaluation of the gravity of the incident → taking of countermeasures.

As follows, we conduct an analysis of the two workflows in case 2 and 3 as aforementioned, in order to make emerge the criticalities of both.

5.1.1 Case 2 – Emergency manageable with Internal means

The case 2 refers to emergencies occurring during working hours, characterized by a moderate level of gravity, sufficiently circumscribed so that they require the only intervention of the Internal Rescue Parties. The evaluation of the gravity of the situation is in charge of the Rescue Team Leader, as noticed in the first workflow analysis: he/she must reach the place of the emergency in the shortest time, making a visual inspection of the site and gather the available data in order to assess the situation status. This activity, as above mentioned, results affected by the time consuming activity of gathering often-poor data, from automatic detectors, people reports, video cameras and distributed smoke sensors when available. Information about the spaces occupancy, possible structural damages and any possible unexpected situations (e.g. the obstruction of some emergency exits for unforeseen causes) are very seldom available or easy to acquire. Therefore, the situation evaluation relies mainly on the data that are immediately at the disposal of the Team Leader. Moreover, until the Team Leader or one of his/her delegates has evaluated the situation, the building occupants are not allowed to evacuate neither to take any countermeasures, in a quite limiting manner when instead, the fire phenomenon is rapidly increasing.

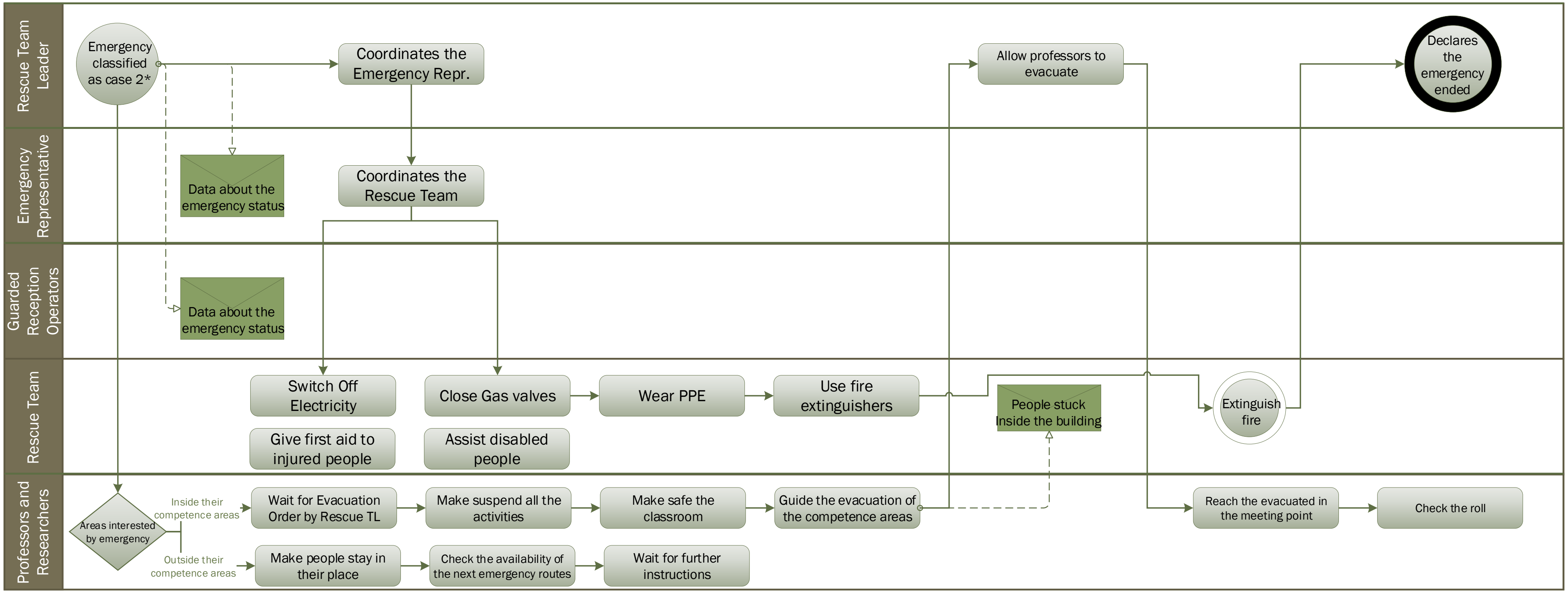


FIGURE 26. EMERGENCY WORKFLOW DURING WORKING HOURS - CASE 2

We can also point out that the verification of the evacuated people against the ones that are stuck in the building results poor and inefficient, since it relies only on the check roll activities conducted by the professors, researchers and responsible of laboratories only once they have evacuated as well. It can be noticed that these actors are the last allowed to leave the spaces of their competence (namely classrooms and laboratories), only after a formal communication received by the Rescue Team Leader. This implies two main criticalities:

- the possibility that these actors may find obstacles created by the changing environment (a general worsening of the situation caused by fire and smoke propagation) that could cause a more or less serious delay in their own evacuation process;
- The consequent delayed check roll activity that could cause a loss of information about missing people during the wait for these responsible actors. Moreover, the identification of people still inside the building and their precise position inside, it is absolutely not taken for granted, since usually a predisposed sensor infrastructure is not employed.

The main and worst consequence is that a too rigid workflow and the delay or missing of certain data could be fatal in case of serious fire propagation that may happen after a first assessment of manageable situation. Notwithstanding, this observation represent only a glaring example of inefficiency in the actual workflow. We generally retain that the current workflow provides a set of instructions to be strictly executed without leaving room for the flexibility necessary to face unforeseen events that may occur in every phase of the standard operations, seriously affecting their success.

5.1.2 Case 3 – Emergency manageable with External Rescue Bodies interventions

The last case is characterized by the higher level of gravity, since it refers to an emergency situation that necessarily requires the interventions of the External Rescue Bodies, at least the Fire Department. All the already discussed critical aspects are present also in this workflow that appears evenly made harsher by a more rigid hierarchy in the operations execution.

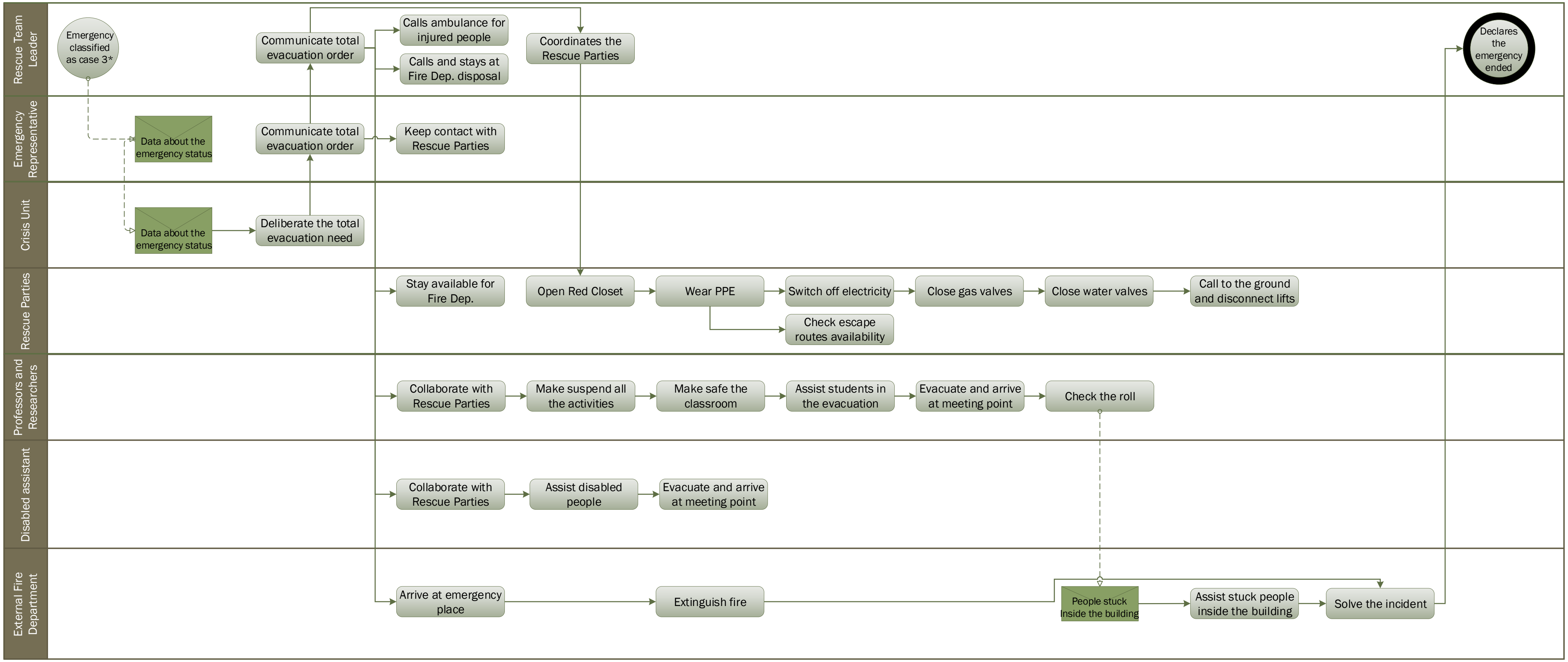


FIGURE 27. EMERGENCY WORKFLOW DURING WORKING HOURS - CASE 3

The hierarchical approach in this case results more evident, with a strong dependency of the actions to the deliberations of the Crisis Unit, the Emergency Representative and the Rescue Team Leader. A more coordinated approach is certainly due to the major gravity of the emergency scenario, especially for the management of a rapidly propagating phenomenon that could also cause injuries and panic to the building occupants. Nevertheless, the bottom-up flow of information about the evolving situation in terms of fire and smoke propagation, structural damages, presence of building occupants stuck in some spaces, as well as the most general happening of unforeseen events results inefficient.

First, the most common buildings are not endowed with specific monitoring systems that could represent an enormous advantage in the data acquisition especially in scarcity of them during rescue operations in harsh environments. Then, the process of reporting information to the higher levels in order to enable the decision making process is time consuming and the top-down decision flow could produce deliberations about actions that are no more effective for the evolved scenario.

The knowledge of the occupants that may have encountered difficulties during the escape that may stuck them inside the building is a relevant aspect: the information deriving from the check roll conducted after the evacuation by the actors in charge at the meeting point, namely the professors and researchers, produces an inacceptable delay for the consequent rescue operations. Another crucial factor is represented also by an often poor or totally absent knowledge of the building itself both by random visitors and Fire Department operators: as highlighted in [134] without a profound knowledge of the spaces, the escape and rescue operations are considerably slowed down and every slow down introduces a delay that may result fatal. It must be noticed also that they can acquire information about the spaces only by the emergency plans hang on walls, which represent a static information mean that does not reflect the evolving situation. Especially during serious emergencies like those that the ones categorized in case 3, damages to the structures as well as unforeseen temporary obstructions to the standard escape routes may occur, profoundly affecting the evacuation and rescue operations.

More precisely, from the emergency plan reported below, we can notice that the only provided vertical connections to be used in a fire emergency scenario are the stairwells A, B, C, D: that means only one stairwell for fire compartment. The use of the other stairwells as well as of the lifts is strictly forbidden since they are not fireproof. Any possible obstructions to reach these connections that may take place in a rapidly changing scenario like the fire one, may invalidate the evacuation.

In conclusion, from the conduction of our analysis of the actual emergency currently in effect we have highlighted the following main weaknesses and criticalities:

- An inefficient information gathering approach that relies basically on poor, incomplete, not easy nor immediate to access data;
- A rigid hierarchical approach , based on a bottom-up information flow accompanied by a top-down decision making process that produce a slow-down in the operations execution and may lead to actions that result ineffective when realized;
- A spread lack of flexibility reflected by a decision making process that begins only after the collection of the data considered necessary, that is a not obvious pre condition to be satisfied since the difficulties in gathering information in the actual approach as mentioned in the first bullet.
- The total absence of consideration of unexpected events and the consequent need of reconfiguration of the rescue operations system makes the intervention architecture easily vulnerable and not able to cope with uncertainties.

The consideration of these weak points in the actual approach, has led us to produce a system architecture with the aim of enriching the actual workflow with the missing elements of flexibility and reactivity, in accordance to the methodology described in chapter 4. Our proposal is to act first on the method, in order to make it more fluid and adaptive to changing situations, then to supply a simulation tool that could help both rescuers and evacuees to search for the information needed at the moment and to investigate alternative solutions in a near real-time manner.

5.2 THE EUSTACHIO SYSTEM ARCHITECTURE

According to our methodology principles, as explained in par. 4.1, our research group has developed a system architecture aimed at supplying the necessary flexibility and reactivity to the system in case of unexpected events. Our goal is not to substitute the actual approach, foreseen by norms, rather to enhance the information flow and the decision making process in case of unforeseen events.

The specific architectural principles, taken into consideration to build up this novel approach are the following:

A. Increasing the efficiency in the data collection, exploiting general data that are commonly available, yet not considered in this point of view.
B. Enhancing the data acquisition with the proposal of employment of automatic data gathering and analysis;
C. Enabling the search of alternative solutions to the standard planned measures when these are not applicable;
D. Making the workflows more fluid by leveraging the autonomy of the lowest levels of the hierarchy promoting a holonic management approach.
E. The "emergent collaboration" characteristic of the system has been implemented, in terms of a behaviour of the single agents that tends to the fulfilment of a common objective, although they are not provided with a complete view of the system, but limited to their own radius of the visible.

The functional blocks generally described in chapter 4 have constituted the system architecture that has found in this phase more specific definition, also in the selection of the tools to employ, embodying the aforementioned architectural principles.

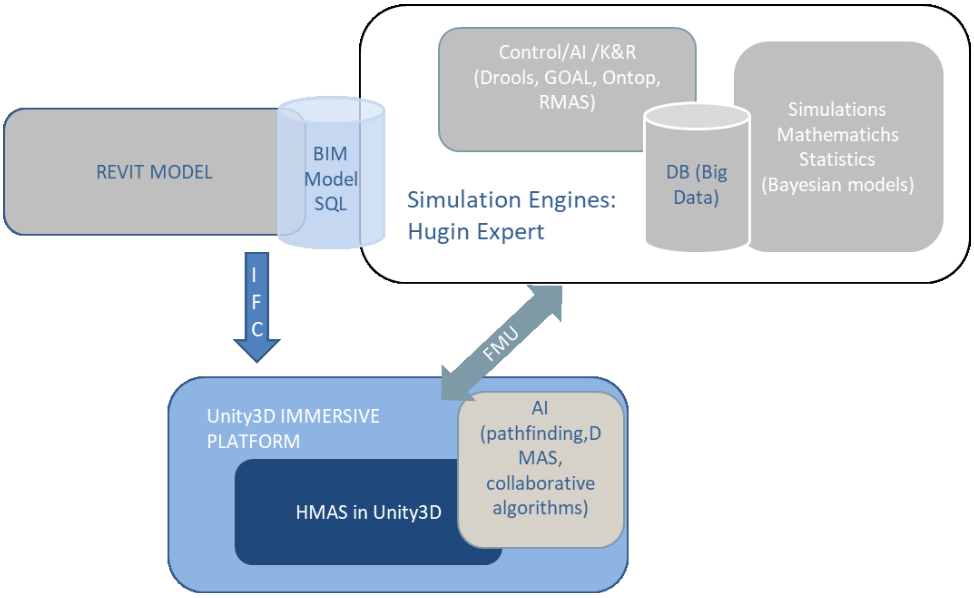


FIGURE 28. EUSTACHIO SYSTEM ARCHITECTURE

In the following paragraphs, a deep description of the functional blocks of the system architecture, developed to concretize our methodology's milestones is provided.

5.2.1 GENERAL DATA EXPLOITATION – BIM MODELS

The first two points of our architecture regarding the data acquisition have been embodied by the employment of the BIM model block and part of the simulation engines.

A BIM model of the Eustachio building, its surrounding and topography have been developed. The model provides information about the geometry and material of the building elements, along with the indication of the locals distributed into the building. It has been realized in LOD 500 according to AIA BIM protocol [135], since it reproduces the as-built of the Eustachio complex.

One of the main characteristic of BIM models is their great interoperability with other software that promote the interchange of a huge amount of topological and semantic data about buildings, aimed at several purposes. Due to its greatly diffused use in the practice, so the ease in the utilization and method reproducibility, accompanied to a wide compatibility of the software to many BIM standard, Autodesk Revit has been selected as the most suitable BIM tool. The model has been created starting from the geometrical information politely made available from the Department of Building Development and Management of Polytechnic University of Ancona.

It reproduces the most updated as-built version of the building in order to give the most realistic picture of the real environment.

Although Autodesk Revit provides the common interchange FBX format and other documented sources have developed specific API REST [9], we have realized the seamless integration among the BIM model and the serious virtual game engine, building up a specific tool, defined “IFC loader”. It allows importing contextual, geometrical, material properties data from the BIM model once exported in IFC format. It consists in an Asset for the virtual reality engine, constituted by several C# scripts aimed at importing the main data from the IFC model. This tool allows also the automatic update of the data in the virtual engine whenever a modification is made in the original Revit model.

The use of the BIM models has been devoted to two main purposes:

- First, a natural usage of a more precise and comprehensive set of data about the built environment that allows extracting topological information, operating as a provider of the geometric properties. In this sense, the use of BIM models is finding a great employment also as communicating means: Wang et al. in [134], propose the use of dynamic panels that represent the building as a 3d model where the available escape routes are indicated in different colours.

  This tool allows representing a strongly more intuitive mean of information communication to the evacuees respect to the common emergency plans that do not provide the possibility to be updated on the basis of the actual availability of escape resources. We retain that the same principle could be applied to test the system in a real case.
- Through the implementation of a holonic system, we propose a **semantic enhancement**, by supplying a further meaning of the BIM objects contained in the model. Referring to the PROSA holonic architecture mentioned in the third Chapter, resource holons are entities characterized by their utility, quantity and availability in a processing environment. In the emergency management, the processing environment is constituted by the building where the emergency has taken place. The resources correspond to the physical entities that can be exploited for the evacuation purpose, they are therefore constituted basically by the escape routes, the emergency exits, the meeting point, the fire extinguishers, in general the “standard means” predisposed for the evacuation aim. In our novel approach, we propose the use of not standard resources in alternative ways, in order to fulfil the evacuation goal. Therefore, “common” BIM object that were not explicitly created for the evacuation/rescue purpose acquire a different

meaning in our virtual environment that produces a proper semantic enhancement respect to their native scope. Examples may found in scenarios where internal doors constitute the unique element of connection among adjacent space that allow reaching fireproof stairwells in case of obstruction due to smoke or generic obstacles to the standard escape routes and emergency exit. Windows and vertical shafts in other cases may constitute the only exploitable means to go outside the building looking for rescue.
As stated before, the representation of all the unexpected events that may occur is not feasible nor reproducible with reasonable time and computing effort, since it represents an NP-hard problem.
Consequently, in order to be real-time effective and decisive, the search of alternative solutions must be triggered only when unexpected events occur and has to be conducted searching for all the possible entities that could be used as resources: in this sense, almost every BIM object may become a resource in the holonic meaning.

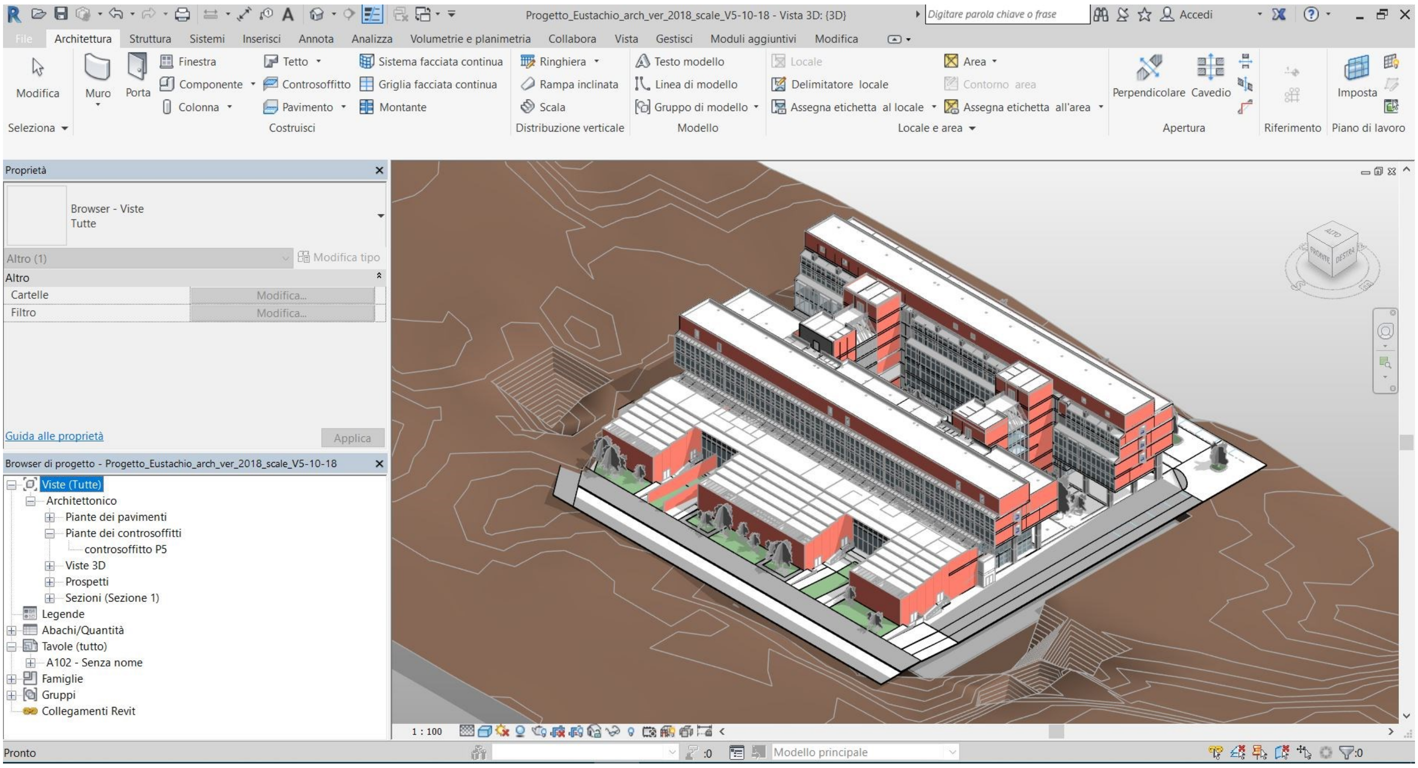


FIGURE 29. EUSTACHIO REVIT MODEL - 3D VIEW - SOUTH EAST SIDE

5.2.2 AUTOMATIC DATA COLLECTION- SIMULATION ENGINES

The employment of simulation engines has allowed integrating several automatically collected data into the virtual engine: as mentioned at point B of this chapter, we have proposed to enhance the information flow by providing real-time data automatically acquired. In the specific case of a fire scenario, the main information to be gathered as support of the rescue operations are clearly represented by the ones concerning the phenomenon evolution (mainly fire and smoke propagation) and the presence of people inside the building. Therefore, we assume that the integration of data coming from thermal and infrared cameras, as well as from real-time location systems (RTLS) deriving from sensors widespread distributed inside the building could provide an enormous support in the emergency management operations.

The automatic collection of data coming from distributed sensors would first considerably reduce the time spent in the activity of seeking for information on site, currently conducted by the Rescue Parties. Then, it would give access to information, whose acquisition cannot be taken for granted due to its high level of inaccessibility: e.g. it is not immediate neither easy finding the presence of people entrapped into the building during a fire scenario.
In this case a RTLS would constitute a valid support to locate people still inside in the building giving a sufficiently refined information about their position, depending on the utilized technology and resilience to the failure of some devices [10].

5.2.3 Application of the holonic theory – Virtual Reality Platform and Bayesian engine

The holonic system has been realized by the use of a serious virtual game engine, providing the virtual environment where the experiment has been conducted. The virtual reality engine has constituted the collector of information coming from BIM models and simulation engines and the test bed for the implementation of the holonic architecture by the means of Artificial Intelligence introduced in the multi-agent system realized.

Unity 3D engine has been selected as the most suitable tool because of the following characteristics:

- high interoperability with other software, including the capability to integrate several functional mock-ups afferent to different engineering disciplines;
- presence of a Physics engine that provides physical behaviour to the components of the simulation, basically the correct acceleration and the affections by collisions, gravity and other forces, making the simulation of a great likelihood with the real world;
- the easily possibility to introduce Artificial Intelligence by programming the agents (the "characters") with several methods: C#, Java scripts or by the mean of visual programming.

In our specific case study, the interconnection with Autodesk Revit software employed to create the BIM model of the building has been realized through the "IFC Loader" tool as described in the previous sections, while the integration of external simulation engines has been realized through specific importing tool.

The AI has been specifically introduced in order to realize two main purposes:

- to simulate the delegate agents that search for information about the environment when required by an unexpected situation, namely the "exploring ants";
- to simulate the delegates that are sent in search for alternative solutions according to a holonic approach. Specific tools provided by Unity 3D asset stores have been tested in order to evaluate their effectiveness in our fire scenario simulated in the Eustachio building, the outcomes of these tests is reported in the following section.

5.3 TESTBED DESCRIPTION

The above-described architecture has been implemented in order to test the system feasibility and features. A fire scenario during working hours of the most severe type, case 3 according to the actual specific emergency decree, has been simulated in the virtual platform built up in Unity 3D.

In order to test the system resilience to unexpected events, we have hypothesized and tested different scenarios that present obstructions to the standard rescue and evacuation operations. In this way, the system has been forced to find alternative solutions in order to fulfil the general requirement of evacuation from the building.

As an example, the building occupants in the yellow area can use only the door highlighted in red to have access to the fireproof stairwells, according to the emergency plan and to a superficial analysis of the morphology. Consequently, if for any possible reason the passage through that door, the building occupants located in that area risk to remain trapped, especially if they do not have a profound knowledge of the building where they are located. In fact, a not negligible aspect in public buildings is the poor awareness of the spatial distribution, since random visitors may have access for general purposes, such as attending lectures, invitational conferences or demonstrative seminaries in laboratory and so far.

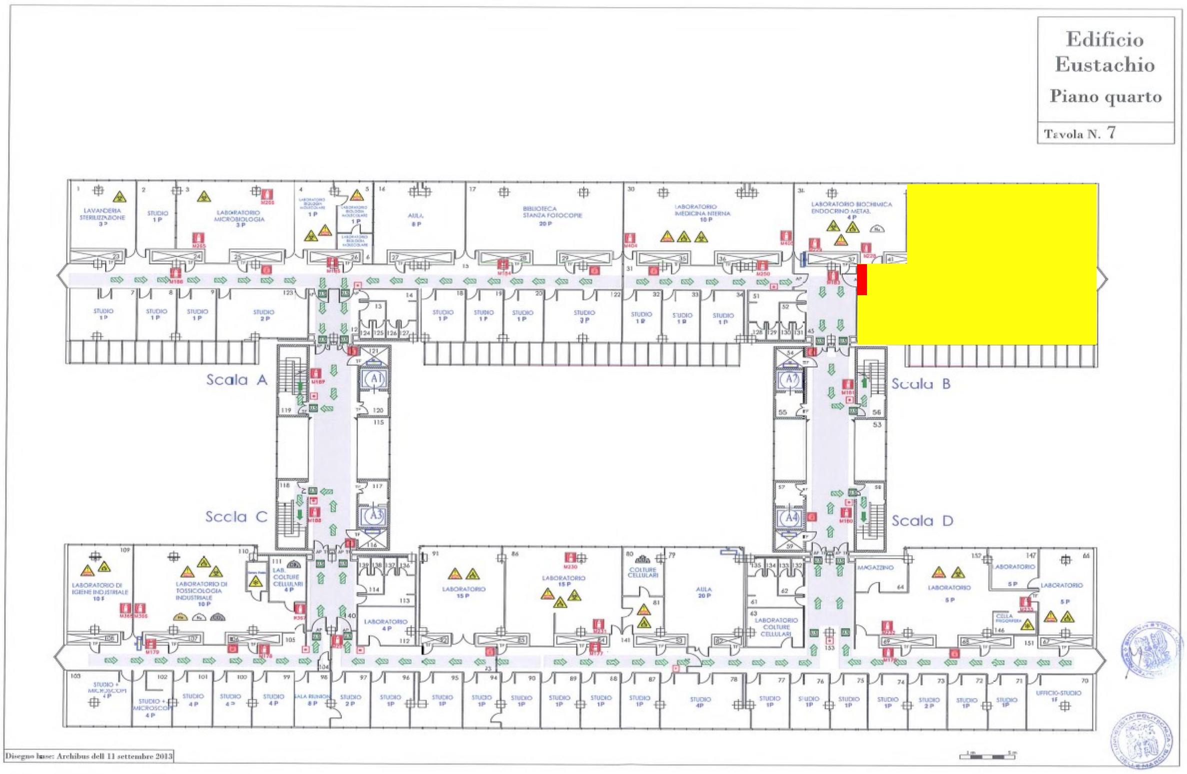


FIGURE 30. EXAMPLE OF UNEXPECTED SCENARIO

Actually, applying a broader look to the plan, it can be noticed that an internal passage through the blue-highlighted space could guarantee to reach the fireproof stairwells, bypassing the obstruction of the red door, from the green circle to the blue one.

FIGURE 31. EXAMPLE OF NOT INTUITIVE ALTERNATIVE PATH

It has to be considered that during emergency scenarios, building occupants are seriously affected by panic and in general lack the necessary clarity of mind for searching alternative solutions if the main emergency plan is for some reasons failing. Moreover, as mentioned in par. 2.1, the actual emergency plans remain plan-text documents, not of immediate comprehension especially in presence of smoke spreading. Therefore, a simple and quite natural search for an alternative path like the one reported as example cannot be taken for granted since it could results harsh in emergency conditions.

Supposing to be in a similar scenario, we have tested several methods to simulate the search of alternative paths, by the means of pathfinding algorithms, intended as enabling methods to find the best paths between two points, navigating the game world of Unity 3D. The native Unity3D algorithms of NavMesh and A* Pathfinding Project Pro have been tested in a simplified model, in order to assess the best method to apply to our research.

The outcomes of the attempts is reported below.

Unity NavMesh Agent

Unity default solution is the NavMesh. According to the review cited in [136], it fits best with simple games without special pathfinding requirement. This process is defined as “NavMesh Baking”. Its implementation consists in collecting the Render Mesh and Terrains of all Game Objects, fundamental objects in Unity that represent characters, props and scenery acting as containers for Components that implement the real functionality, marked as “Navigation Static”. The collected Game Objects are processed to create a navigation mesh that approximates the walkable surfaces of the level. The NavMesh represents the area where the centre of the agent can move, for run-time efficiency purposes, providing the designers with a first glance of the spaces where an agent can move through gaps, independently from its radius, therefore their output approximates the walkable surface.
A first evident criticality we have encountered is that the mesh is “baked” in advance, so it cannot be changed at runtime. Hence, the Unity NavMesh cannot handle procedurally generated game world and there are some performance issues with dynamic obstacles and massive amount of units in the scene.

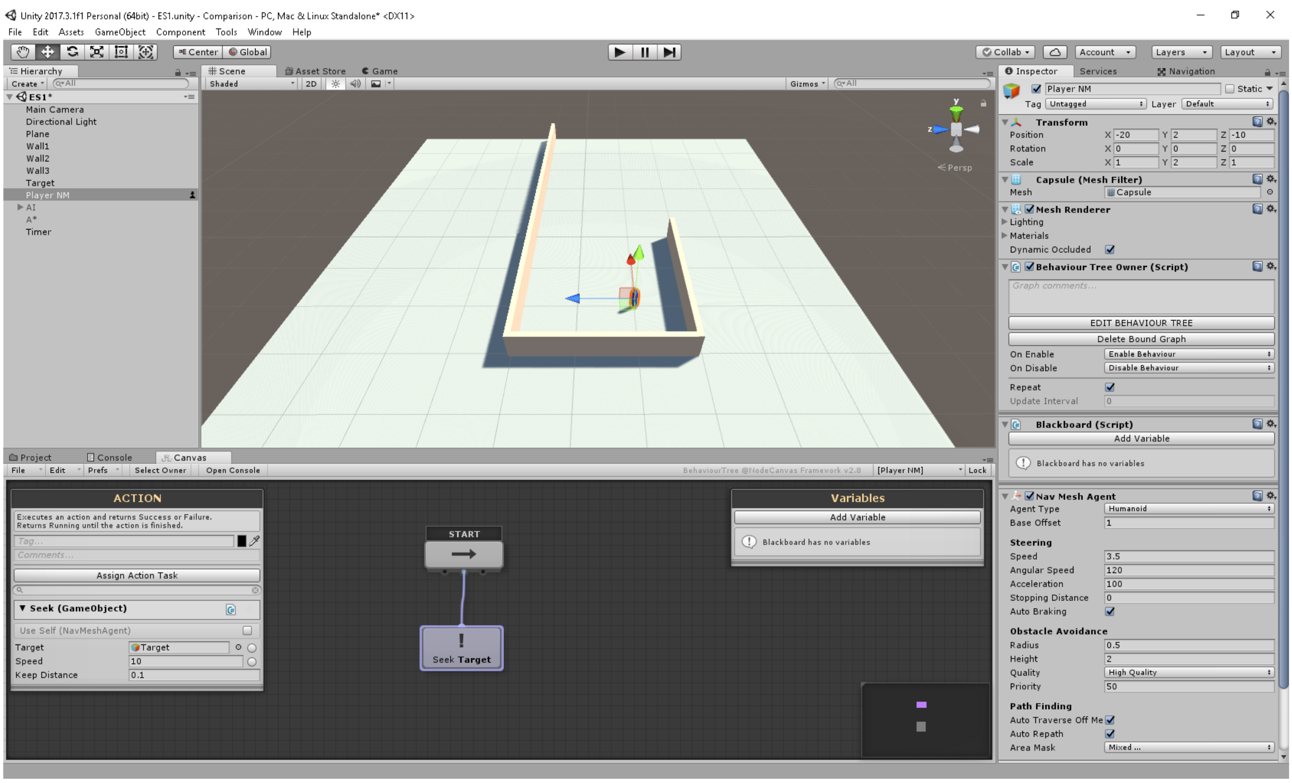


FIGURE 32. IMPLEMENTATION OF UNITY NAVMESH ALGORITHM

A* Pathfinding Pro

A* Pathfinding Project Pro is one of the most popular dedicated pathfinding Unity asset and, according to the review above, the benchmark for quality pathfinding in Unity. Unlike Unity NavMesh Agent, it supports dynamic updates of the graphs at runtime.
It offers a selection of different navigation graphs (Grid, Layered Grid, NavMesh, Point and Recast Graph), plus various types of path post-processing and local avoidance in both the XZ and XY planes. [136]

- The "Grid Graph" lacks support for worlds, which have multiple layers, such as a building with multiple floors. The "Layered Grid Graph" supports the same features of the grid graph, but also multiple layers, involving major time due to a major use of memory.

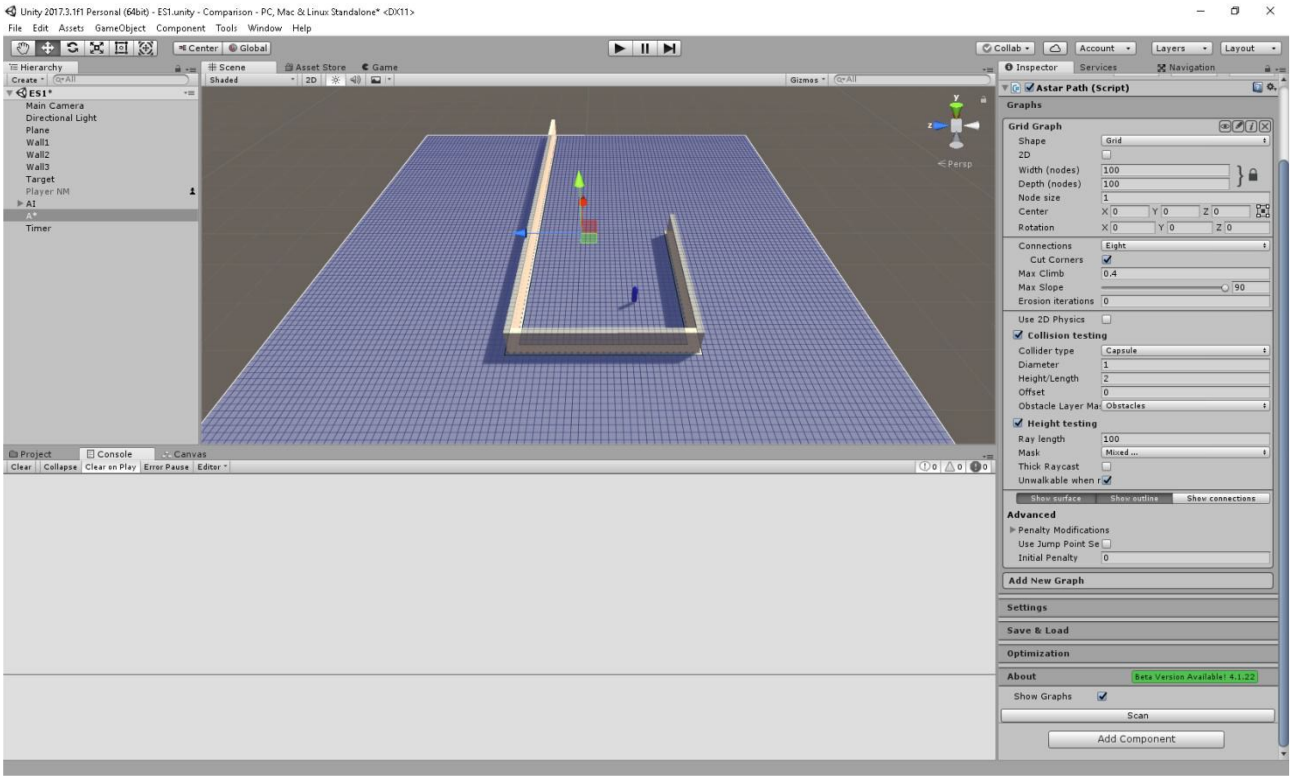


FIGURE 33. IMPLEMENTATION OF UNITY A* PATHFINDING GRID GRAPH ALGORITHM

- Navmeshes are meshes where each triangle defines a walkable area (see Figure 34). Polygons instead of points mean assure a really nice looking paths and the graphs are also really fast to search and have a low memory footprint because fewer nodes are usually needed to describe the same area compared to grid graphs.

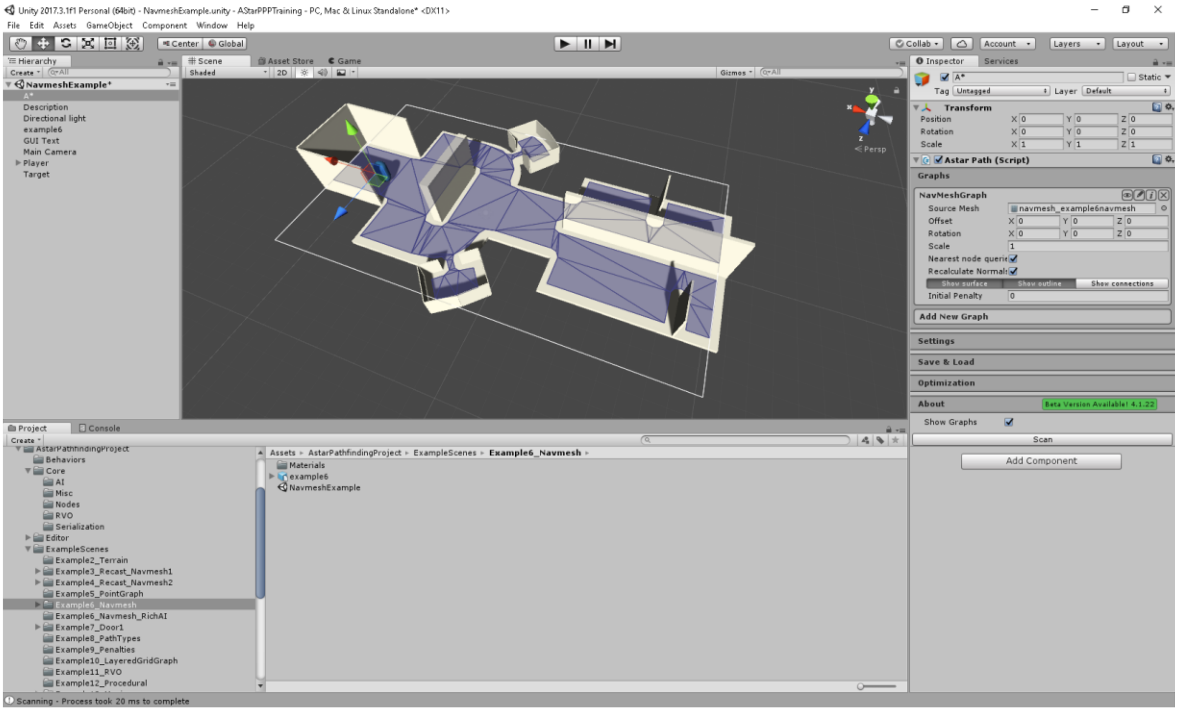


FIGURE 34. IMPLEMENTATION OF UNITY A* PATHFINDING NAVSMESH ALGORITHM

- The “Point Graph” is the most basic graph structure, consisting of a number of interconnected points in space called nodes or waypoints (see Figure 35). The point graph takes a “Transform” object as "root", this “Transform” will be searched for child objects, every child object will be treated as a node. If recursive is enabled, it will also search the child objects of the children recursively.

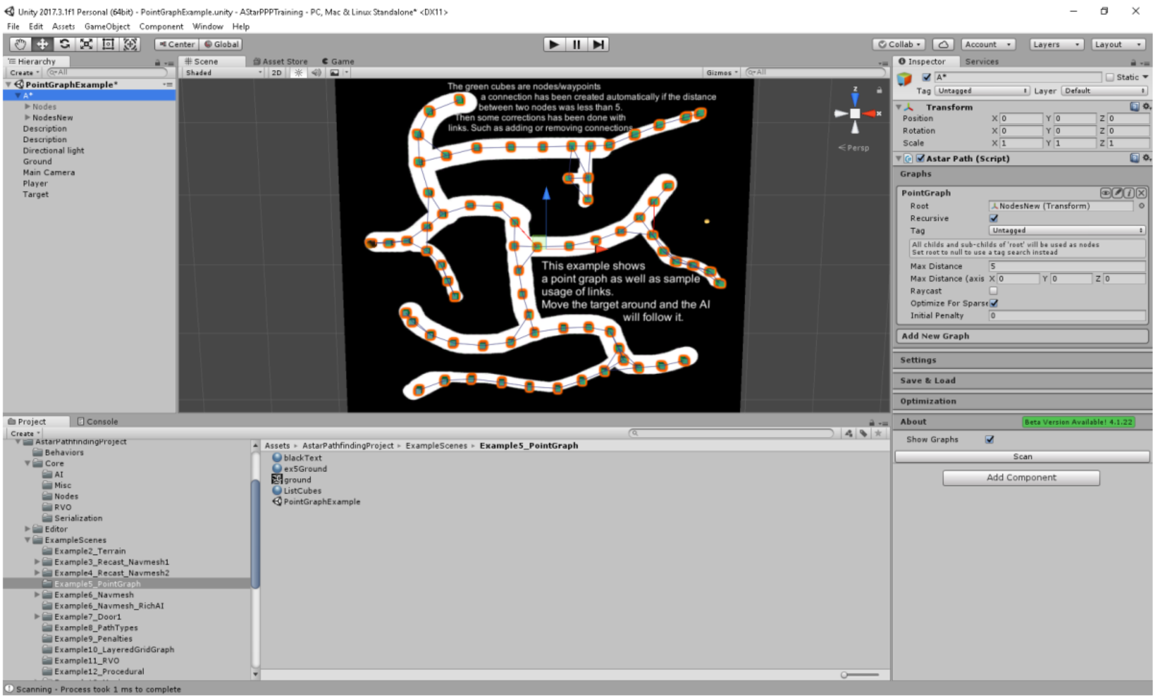


FIGURE 35. IMPLEMENTATION OF UNITY A* PATHFINDING POINT GRAPH ALGORITHM

- The "Recast Graph" automatically generates Navmesh graphs based on world geometry (contrarily "Nav Mesh Graph" inside A* Pathfinding Project Pro requires to drag and drop a specific NavMesh for the game world).

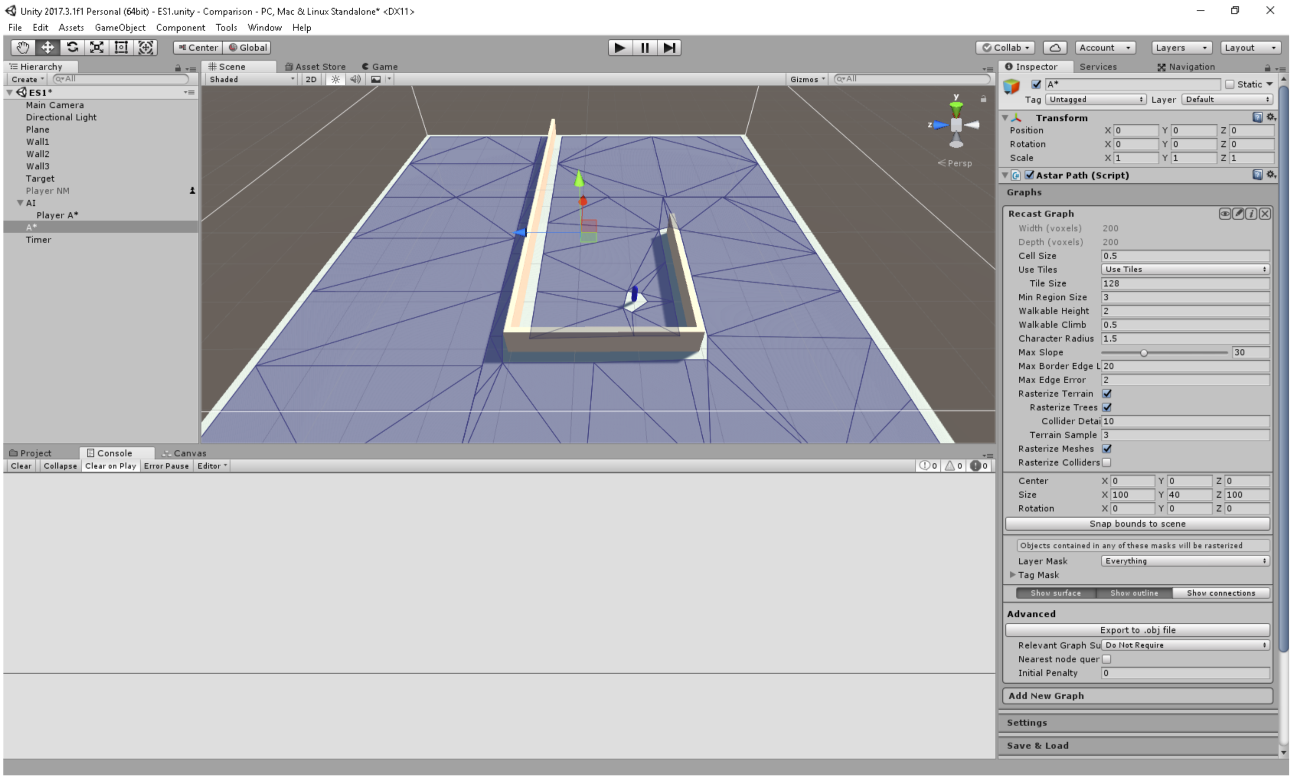


FIGURE 36. IMPLEMENTATION OF UNITY A* PATHFINDING RECAST GRAPH ALGORITHM

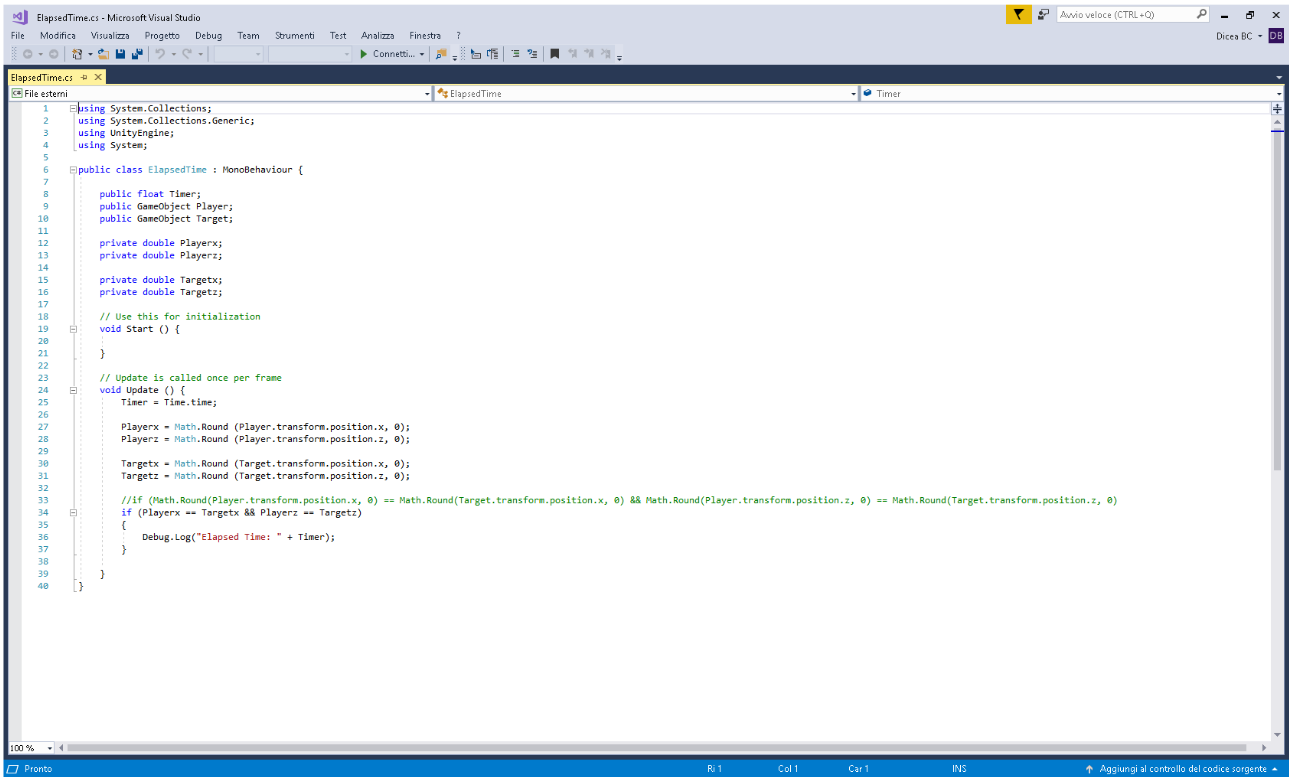
UNITY NAVMESH AGENT VS A* PATHFINDING PROJECT PRO OUTCOMES

The two methods' efficiency has been evaluated measuring the time the player takes to reach the target. The same Target's and Player's positions are considered among the scenarios for each iteration, as well the same "Max Speed" (10), "Max Acceleration" (100) and "End Reached Distance" (0). The player position is (-20.0, 0.0, -10.0) for each iteration.

	Elapsed Time [s]		
Target Transform Position	Unity NavMesh Agent	A* PPP (Grid Graph)	A* PPP (Recast Graph)
(-9.9, 0.0, -24.3)	3.717835	4.202618	4.184528
(27.5, 0.0, -43.0)	6.088444	6.438555	6.366143
(35.9, 0.0, 34.0)	16.00065	16.47642	17.12864

FIGURE 37. CALCULATION OF ELAPSED TIME

The “Timer” is an empty gameobject, which contains the script “ElapsedTime” (see Figure 37), created ad hoc in order to measure the time the player takes to reach the target and compare the two solutions’ efficiency.



```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using System;

public class ElapsedTime : MonoBehaviour {

    public float Timer;
    public GameObject Player;
    public GameObject Target;

    private double Playerx;
    private double Playerz;

    private double Targetx;
    private double Targetz;

    // Use this for initialization
    void Start () {

    }

    // Update is called once per frame
    void Update () {
        Timer = Time.time;

        Playerx = Math.Round (Player.transform.position.x, 0);
        Playerz = Math.Round (Player.transform.position.z, 0);

        Targetx = Math.Round (Target.transform.position.x, 0);
        Targetz = Math.Round (Target.transform.position.z, 0);

        //if (Math.Round(Player.transform.position.x, 0) == Math.Round(Target.transform.position.x, 0) && Math.Round(Player.transform.position.z, 0) == Math.Round(Target.transform.position.z, 0)
        if (Playerx == Targetx && Playerz == Targetz)
        {
            Debug.Log("Elapsed Time: " + Timer);
        }

    }
}
```

FIGURE 38. TIMER GAME OBJECT SCRIPT

Considering that the times to reach the target (“Elapsed Time”) for the two pathfinding solutions are similar and the A* Pathfinding Project Pro’s highest potential, according to the reported review, the latter Unity asset seems to be the best choice than the default NavMesh Agent.

The conduction of the experiment has focused also on the implementation of the emergent cooperation with the aim of testing the cooperation among the characters, since the capability of the holons to cooperate in temporary associations, namely the holarchies, is a milestone of our research.

As follows, a full description of the conducted experiments along with the evident results obtained is provided.

The concept of “emergent cooperation” can be described using a metaphor: the behaviour of these agents is similar to the one belonging to the birds of a flock; no one is able to manage flock’s shape and dimension, but everyone takes care of maintaining flock’s trajectory, flock’s speed and minimum distance from its fellows. Although no one of the birds has a complete view of the scene, the behaviour described above is the result of an “emergent collaboration”. This kind of cooperation is not so onerous for birds because it is supposed to be integrated within their DNA and, therefore, instinctive. The same functioning characterizes the agents inside the developed architecture.

On the basis of the PROSA reference, we have envisioned different layers corresponding to resource, product and order holons that interact together. The different layers interact each other with a publish/subscribe scheme, whose central concept is the topic: each node/layer in the architecture, subscribes and some other publishes information on the topic. All the information in the process is published to actors and any controller and optimizer can be built over the infrastructure and its semantic abstraction as a plug-in. In our vision, the several layers act like a human being that only subscribes to interesting events/information and publishes relevant events or information, which are specifically useful for the occurring situation, complying with the actual needs. [137]

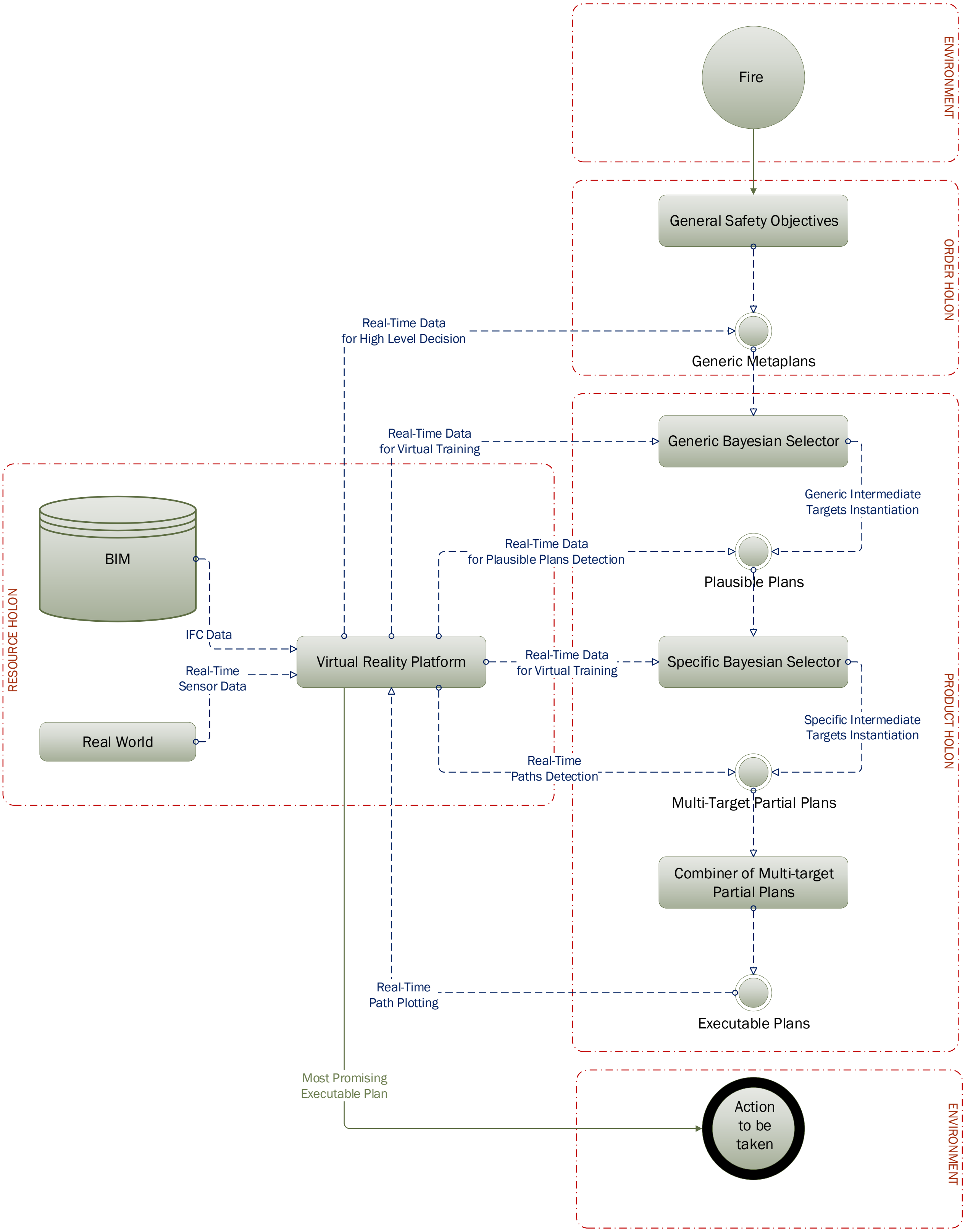


FIGURE 39. ARCHITECTURE DEVELOPED TO EMBODY "EMERGENT COOPERATION"

More specifically:

- The real scenario constitutes the **environment** in which the holons operate, namely the fire occurring and the countermeasures to be taken at end of the process of elaboration of unconventional solutions.
- The entities represented in **virtual reality platform** through the collection of topological data from IFC models and about the evolution of the system by the real-time monitoring on site, correspond to the **resource** holon, which corresponds to a resource in the underlying processing environment, which it reflects in the planning system. A resource, in the planning environment, is an entity characterized by it utility, quantity and availability in a processing environment.
- The **product holon**, is represented by the **Generic** and **Specific Bayesian Selector** and by the **Combiner of Multitarget Partial Plans**, since they hold the technical knowledge to execute a process and provide a valid sequence of operations to execute it with an increasing level of accuracy. Moreover, they provide operation details to the resources, evaluating the quality of execution.

The developed architecture (Fig. 39) is applied to manage the emergency scenario due to the fire inside a building. The key feature of this architecture is that the resulting system is applicable for every building, without the need to configure it manually every time.

General Safety Objectives

The highest layer of the architecture is fed with real-time data by the virtual reality platform, in order to elaborate high-level decisions, namely generic metaplans that may be generally applicable and are independent from the specific type of building. The output of this elaboration are the general processes to be executed (the order), that may be represented by the generically instruction “stay in/go out” and are published to the following layer.

Generic Bayesian Selector

The “Bayesian Selector” is a Bayesian network, which produces the instantiation of generic intermediate targets, on the basis of the real-time data supplied by the virtual reality platform for the virtual training. The main output of this layer are plausible plans based on the topological aspects of a generic building, with medium-level objectives.

The “Generic Bayesian Bettor”, gathering data from agents released inside the building digital environment, considers the building's frontiers towards which lead people in order to save them. The upper and side borders are the possible frontiers towards alternative ways out. The technology described in [138] and [139], on the basis of data gathered from agents released inside the building digital environment, is able to instantiate “Plausible Plans” in real-time.

Examples of plausible plans may be: “Lead people to the roof and pick up them by a helicopter”, “Lead all people to the window and pick up them by a ladder truck”, “Lead all people to the window and pick up them by a normal ladder”, “Lead all people to the window and use a slide”.

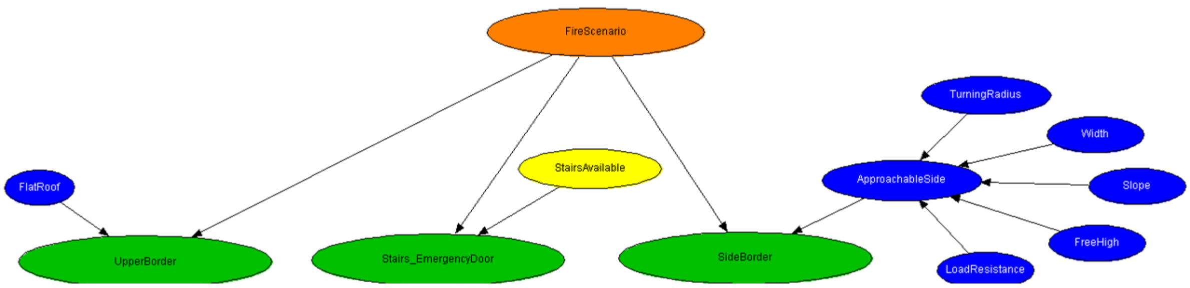


Figure 40. GENERIC BAYESIAN SELECTOR

Specific Bayesian Selector

The “Specific Bayesian Selector” receives a set of plausible plans from the generic one and adapt them to a set of plans for the building of the specific case of study on the basis of the data concerning it, received by the virtual reality platform.

The complete network named “Specific Bayesian Bettor” evaluates which “Plausible Plan” can lead people out safely with the highest probability, producing a set of multi-target partial plans by the means of specific intermediate targets instantiation, that evaluate the possibility of execution of each plan relying on resources’ availability.

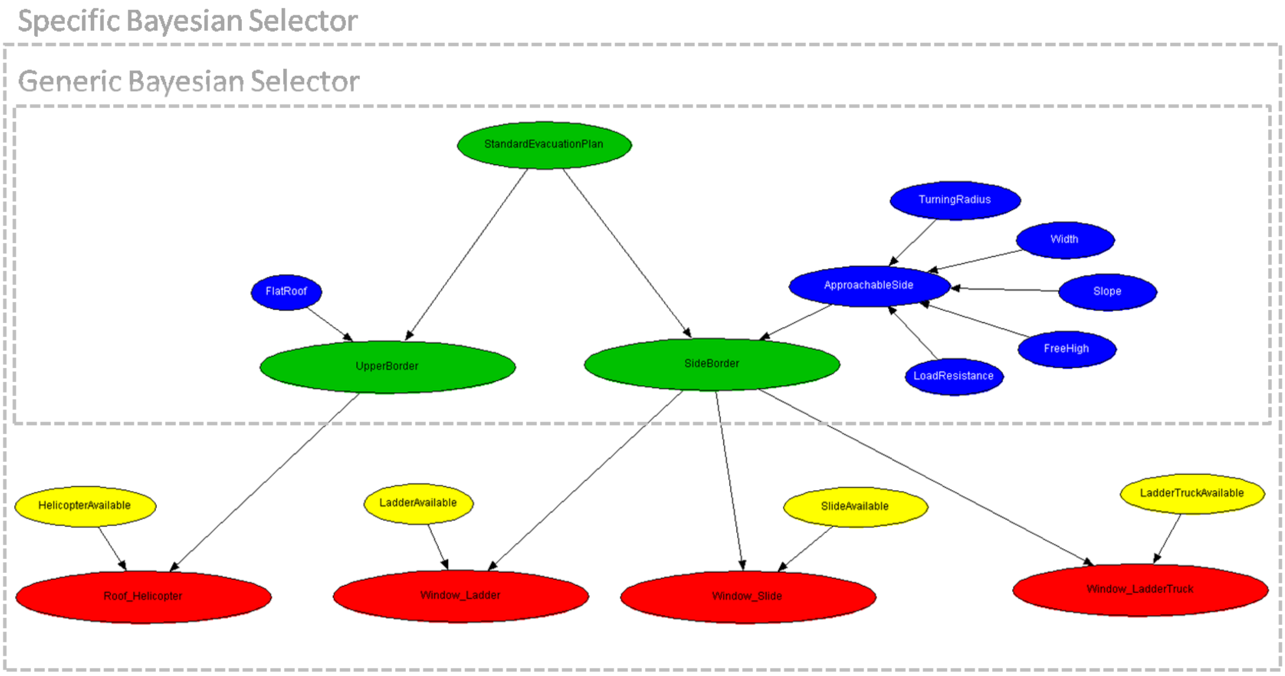


FIGURE 41. BAYESIAN NETWORKS DEVELOPED FOR GENERIC AND SPECIFIC SELECTORS

As can it be noticed in Fig. 41, the plausible plans produced by the higher level of the Generic Bayesian Selector may be the leading evacuation towards the upper or the side borders, on the basis of the evaluation of their enabling resources:

- presence of a flat roof in the first case
- presence of an approachable side on the other case, in turn, depending on the characteristics that define, according to the specific Safety Norms, a side as "approachable" by fire departments' vehicles (width, free height, turning radius, slope, load resistance, respectively of at least 3,5m, 4m, <10%, 20t). [140]

If both plans are considered as plausible on the basis of their level of probability, the Specific Bayesian Selector is then demanded to execute specific intermediate instantiations regarding multi-target partial plans, e.g. in the case of the approachable side, the evaluation of three different solutions is provided: the use of a window ladder, a slide or a ladder truck.

The calculated probability of execution of these partial plans, based on the involved resources' availability, are published to the last layer in order to be exploited.

COMBINER OF MULTI-TARGET PARTIAL PLANS

The last layer, the “Combiner of Multi-Target Partial Plans” has low-level objectives and uses the information about alternative partial paths received by the virtual reality platform as real-time simulations, to intermediate points, like windows, roof and so on. Considering the “Plausible Plan” summarized as “Lead all people to the window and pick up them by a ladder truck”, the building’s windows are intermediate points through which can be defined alternative ways out if they are approachable by both users and rescue team. In other words, the “Multi-Target Partial Plans” consider the paths from the user to all the reachable windows (see blue line in Fig. 43, Fig. 44 and Fig. 45) and the ones from the ladder truck to all the approachable windows (see red lines in Fig. 43, Fig. 44 and Fig. 45).

The Combiner has in charge the evaluation of the most promising combination of these multi-target partial plans, which are deriving from the previous layer and subscribed.

The most promising combination is published then to the virtual reality platform with the set of partial plans to be finally simulated and plotted, in order to be presented to the users as the actions to be taken for safety purposes according to the actual situation.

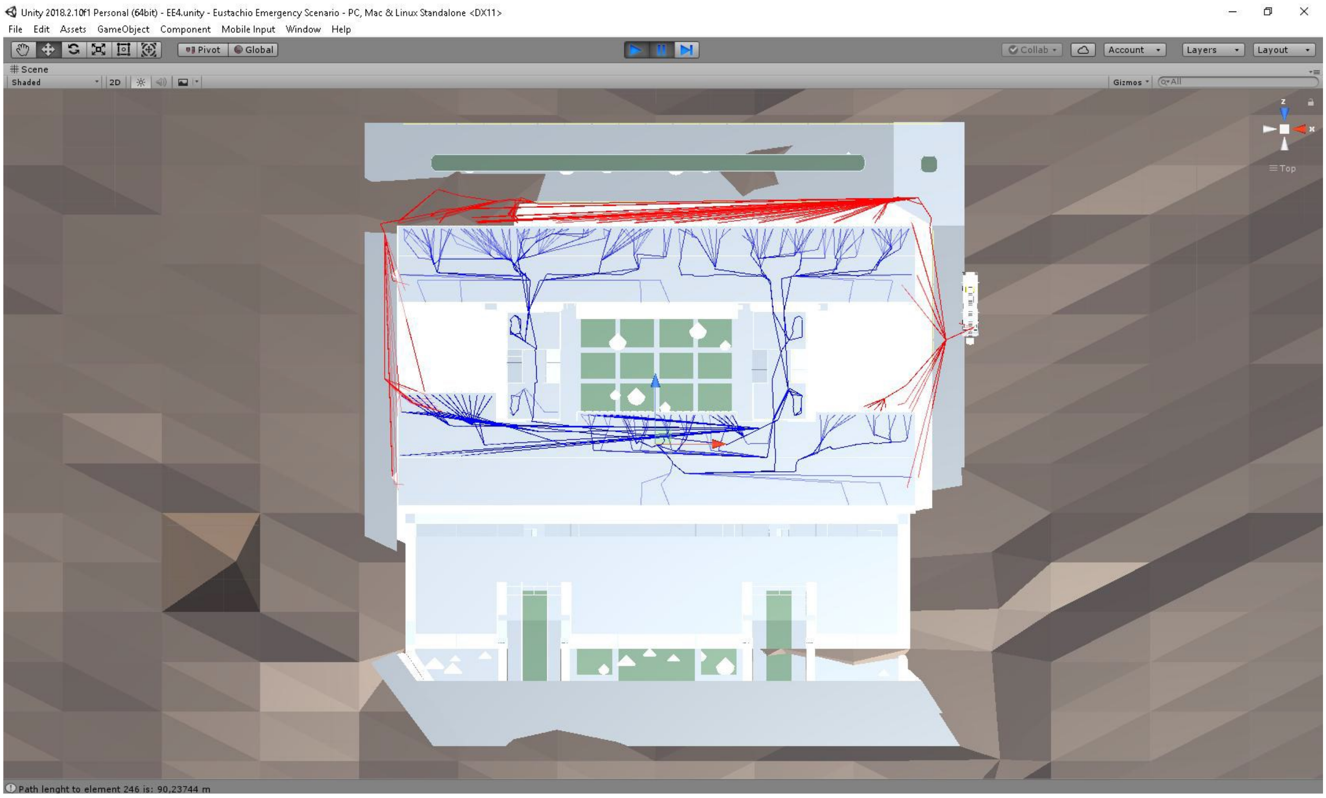


FIGURE 42. CALCULATED PATHS TO REACH AVAILABLE WINDOWS

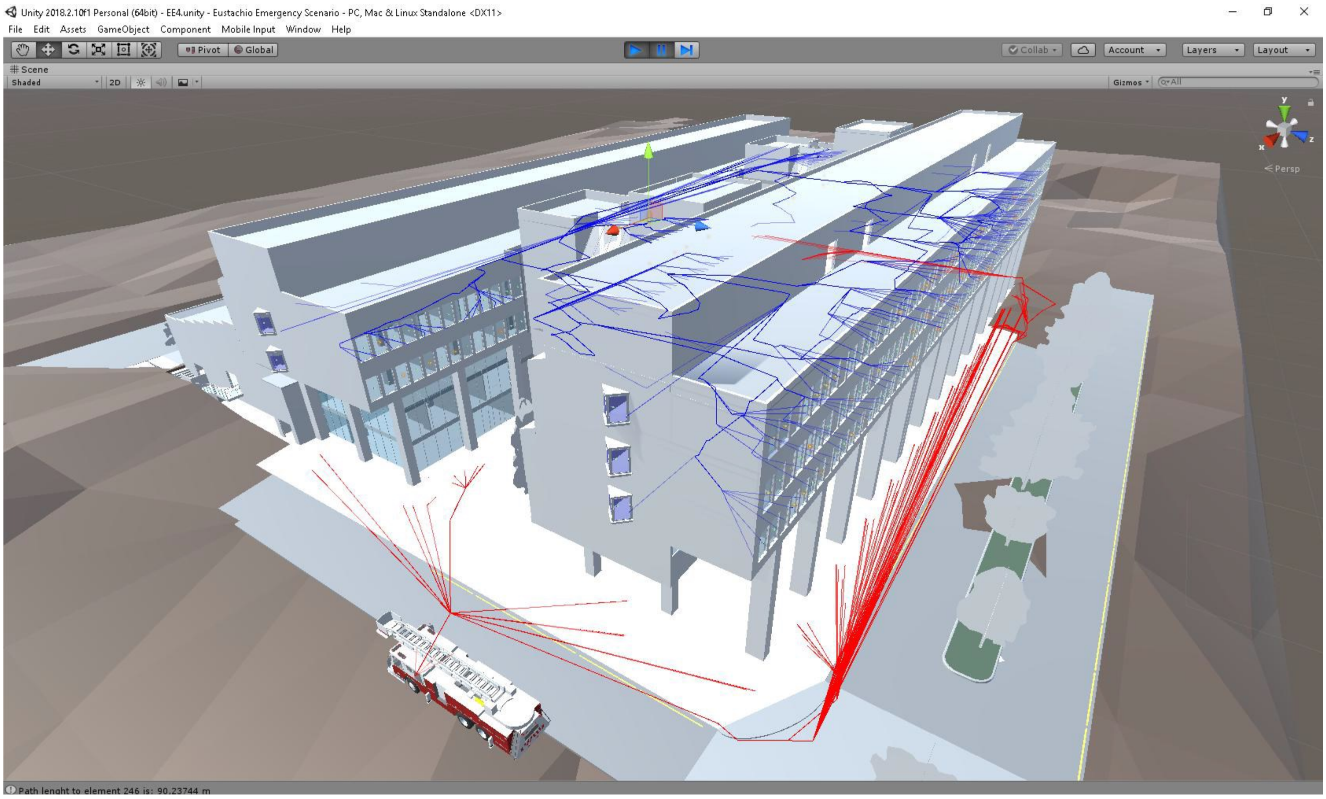


FIGURE 43 CALCULATED PATHS TO REACH AVAILABLE WINDOWS

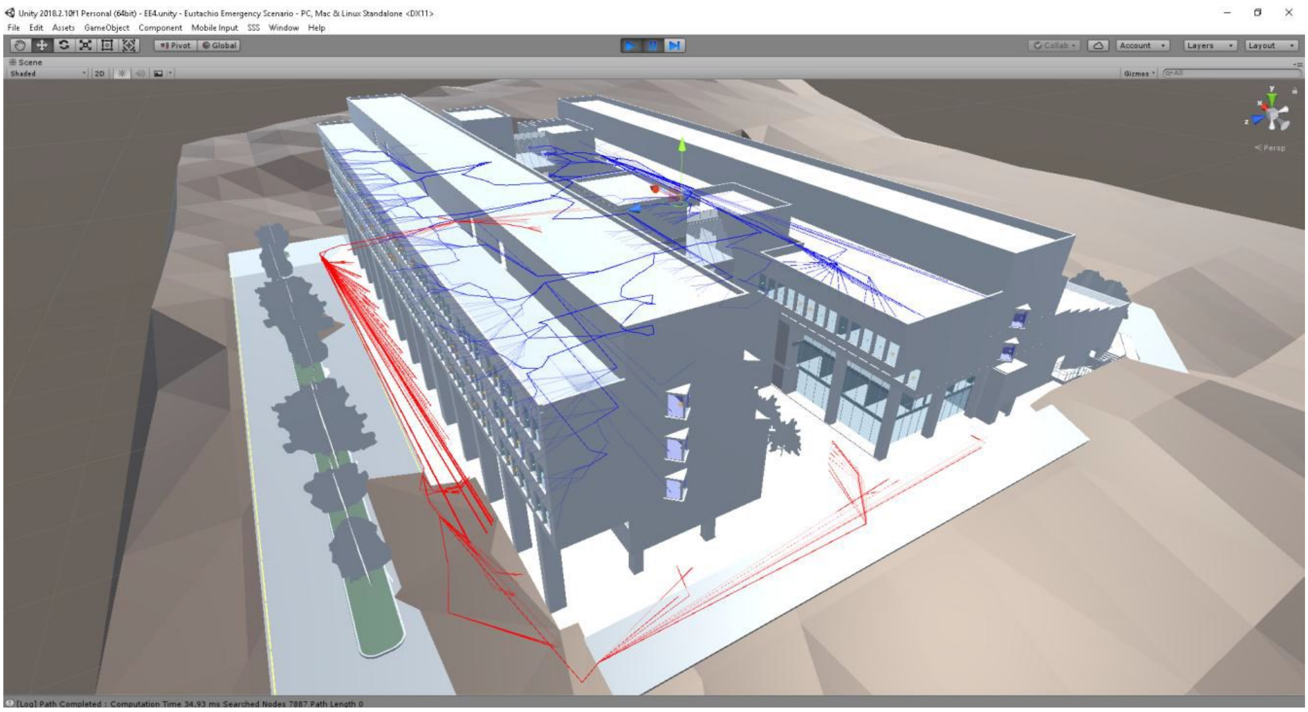


FIGURE 44. CALCULATED PATHS TO REACH AVAILABLE WINDOWS

The windows' positions and the path lengths from both user and rescue team to the building's windows are exported to Excel (see Figure 46) in order to process the data.

Assuming the escape speed of a person during an emergency scenario equals to 1 [m/s], as stated in [141], the escape time can be easily deduced.

5.4 Outcomes

The first cycles of simulations conducted in the virtual reality engine have allowed extracting data about the covered paths length in search of alternative solutions. By assuming the velocity of people during evacuation in the interval of [0,5÷1,2] [m/s] according to literature values [141], information about the shortest paths have been elaborated among a plethora of alternative solutions. This information have been utilized to feed the specific Bayesian bettor, providing resources' availability, in order to select the most suitable executable plan.

TARGET_N	TARGET_GUID	USER-TARGET_PATH[m]	USER_ESCAPE_SPEED[m/s]	RESCUETEAM-TARGET_PATH[m]	RESCUETEAM_SPEED[km/h]	RESCUETEAM_SPEED[m/s]	USER-TARGET_TIME[s]	RESCUETEAM-TARGET_TIME[s]	TOTAL_TIME[s]
225	1Tbr2aQqL9jBsnn$hdGBaw	11,27	1,00	25,56	5,00	1,39	11,27	18,40	29,67
253	37wGNYMZb9mB2SjWfJqJXD	11,27	1,00	25,56	5,00	1,39	11,27	18,40	29,67
224	1Tbr2aQqL9jBsnn$hdGBar	11,47	1,00	25,56	5,00	1,39	11,47	18,40	29,87
252	37wGNYMZb9mB2SjWfJqJXC	11,47	1,00	25,56	5,00	1,39	11,47	18,40	29,87
226	1Tbr2aQqL9jBsnn$hdGBaV	11,49	1,00	25,56	5,00	1,39	11,49	18,40	29,89
254	37wGNYMZb9mB2SjWfJqJXE	11,49	1,00	25,56	5,00	1,39	11,49	18,40	29,89
227	1Tbr2aQqL9jBsnn$hdGBaS	11,55	1,00	25,56	5,00	1,39	11,55	18,40	29,95
228	1Tbr2aQqL9jBsnn$hdGBYD	11,55	1,00	25,56	5,00	1,39	11,55	18,40	29,95
229	1Tbr2aQqL9jBsnn$hdGBYI	11,55	1,00	25,56	5,00	1,39	11,55	18,40	29,95
255	37wGNYMZb9mB2SjWfJqJXF	11,55	1,00	25,56	5,00	1,39	11,55	18,40	29,95
14	1k9n0KaAr6A8uYKOaieQh5	13,23	1,00	25,56	5,00	1,39	13,23	18,40	31,63
302	0vCtCPI_XD1O0dkwBib3s5	40,87	1,00	25,56	5,00	1,39	40,87	18,40	59,27
309	0vCtCPI_XD1O0dkwBib3rK	40,87	1,00	25,56	5,00	1,39	40,87	18,40	59,27
301	0vCtCPI_XD1O0dkwBib3ty	41,38	1,00	25,56	5,00	1,39	41,38	18,40	59,78
308	0vCtCPI_XD1O0dkwBib3rL	41,38	1,00	25,56	5,00	1,39	41,38	18,40	59,78
300	0vCtCPI_XD1O0dkwBib3tz	42,05	1,00	25,56	5,00	1,39	42,05	18,40	60,45
307	0vCtCPI_XD1O0dkwBib3rM	42,05	1,00	25,56	5,00	1,39	42,05	18,40	60,45
299	0vCtCPI_XD1O0dkwBib3t_	42,27	1,00	25,56	5,00	1,39	42,27	18,40	60,67
306	0vCtCPI_XD1O0dkwBib3rN	42,27	1,00	25,56	5,00	1,39	42,27	18,40	60,67
298	0vCtCPI_XD1O0dkwBib38K	43,27	1,00	25,56	5,00	1,39	43,27	18,40	61,68
305	0vCtCPI_XD1O0dkwBib3rG	43,27	1,00	25,56	5,00	1,39	43,27	18,40	61,68
297	0vCtCPI_XD1O0dkwBib38L	44,13	1,00	25,56	5,00	1,39	44,13	18,40	62,54
304	0vCtCPI_XD1O0dkwBib3rH	44,13	1,00	25,56	5,00	1,39	44,13	18,40	62,54
223	1Tbr2aQqL9jBsnn$hdGBdn	7,22	1,00	78,18	5,00	1,39	7,22	56,29	63,51
244	37wGNYMZb9mB2SjWfJqJdU	7,22	1,00	78,18	5,00	1,39	7,22	56,29	63,51
222	1Tbr2aQqL9jBsnn$hdGBci	7,29	1,00	78,18	5,00	1,39	7,29	56,29	63,58
243	37wGNYMZb9mB2SjWfJqJdT	7,29	1,00	78,18	5,00	1,39	7,29	56,29	63,58
221	1Tbr2aQqL9jBsnn$hdG8Sc	8,03	1,00	78,18	5,00	1,39	8,03	56,29	64,32
242	37wGNYMZb9mB2SjWfJqJdS	8,03	1,00	78,18	5,00	1,39	8,03	56,29	64,32
13	1k9n0KaAr6A8uYKOaieQgl	40,86	1,00	33,87	5,00	1,39	40,86	24,39	65,24
288	0vCtCPI_XD1O0dkwBib3B2	53,86	1,00	20,95	5,00	1,39	53,86	15,09	68,95
289	0vCtCPI_XD1O0dkwBib3B1	53,86	1,00	20,95	5,00	1,39	53,86	15,09	68,95
238	1lw7YFAH9EK9AqPA5fd9rt	8,47	1,00	85,64	5,00	1,39	8,47	61,66	70,14
251	37wGNYMZb9mB2SjWfJqJd5	8,47	1,00	85,64	5,00	1,39	8,47	61,66	70,14
237	1lw7YFAH9EK9AqPA5fd9rq	8,50	1,00	85,64	5,00	1,39	8,50	61,66	70,17
250	37wGNYMZb9mB2SjWfJqJd4	8,50	1,00	85,64	5,00	1,39	8,50	61,66	70,17
290	0vCtCPI_XD1O0dkwBib3AZ	53,55	1,00	23,22	5,00	1,39	53,55	16,72	70,27
291	0vCtCPI_XD1O0dkwBib3AY	53,55	1,00	23,22	5,00	1,39	53,55	16,72	70,27
284	0vCtCPI_XD1O0dkwBib3DR	55,94	1,00	20,09	5,00	1,39	55,94	14,46	70,40
286	0vCtCPI_XD1O0dkwBib3DP	55,94	1,00	20,09	5,00	1,39	55,94	14,46	70,40

285	0vCtCPI_XD1O0dkwBib3DQ	55,95	1,00	20,46	5,00	1,39	55,95	14,73	70,68
287	0vCtCPI_XD1O0dkwBib3DO	55,95	1,00	20,46	5,00	1,39	55,95	14,73	70,68
236	1lw7YFAH9EK9AqPA5fd9rr	9,76	1,00	85,64	5,00	1,39	9,76	61,66	71,42
249	37wGNYMZb9mB2SjWfJqJd3	9,76	1,00	85,64	5,00	1,39	9,76	61,66	71,42
1	2uTtCYjBX8vfPYGSXQUCJ6	49,50	1,00	31,60	5,00	1,39	49,50	22,75	72,25
3	2TsP88EyP6tfxMaL$RjJ1f	49,50	1,00	31,60	5,00	1,39	49,50	22,75	72,25
12	1k9n0KaAr6A8uYKOaieQKW	47,95	1,00	33,87	5,00	1,39	47,95	24,39	72,33
294	0vCtCPI_XD1O0dkwBib39X	55,90	1,00	24,30	5,00	1,39	55,90	17,50	73,40
295	0vCtCPI_XD1O0dkwBib39W	55,90	1,00	24,30	5,00	1,39	55,90	17,50	73,40
292	0vCtCPI_XD1O0dkwBib3A1	56,21	1,00	24,00	5,00	1,39	56,21	17,28	73,49
293	0vCtCPI_XD1O0dkwBib3A0	56,21	1,00	24,00	5,00	1,39	56,21	17,28	73,49
296	0vCtCPI_XD1O0dkwBib38M	56,18	1,00	25,03	5,00	1,39	56,18	18,02	74,21
303	0vCtCPI_XD1O0dkwBib3rl	56,18	1,00	25,03	5,00	1,39	56,18	18,02	74,21
262	2js88JN$5FR85qHZtkOQd8	70,49	1,00	25,56	5,00	1,39	70,49	18,40	88,89
230	1Tbr2aQqL9jBsnn$hdGBZ1	70,58	1,00	25,56	5,00	1,39	70,58	18,40	88,99
231	1Tbr2aQqL9jBsnn$hdGBWm	70,58	1,00	25,56	5,00	1,39	70,58	18,40	88,99
261	2js88JN$5FR85qHZtkOQW6	71,29	1,00	25,56	5,00	1,39	71,29	18,40	89,69
257	37wGNYMZb9mB2SjWfJqJWn	72,30	1,00	25,56	5,00	1,39	72,30	18,40	90,70
256	37wGNYMZb9mB2SjWfJqJWm	73,44	1,00	25,56	5,00	1,39	73,44	18,40	91,84
8	1S$XS4sLb7ie56ea0Oao0n	90,85	1,00	18,65	5,00	1,39	90,85	13,43	104,28
2	2uTtCYjBX8vfPYGSXQUCGU	96,29	1,00	18,70	5,00	1,39	96,29	13,46	109,75
281	2js88JN$5FR85qHZtkOQhd	92,09	1,00	25,56	5,00	1,39	92,09	18,40	110,49
282	2js88JN$5FR85qHZtkOQhc	92,35	1,00	25,56	5,00	1,39	92,35	18,40	110,75
11	1k9n0KaAr6A8uYKOaieQGQ	97,97	1,00	17,83	5,00	1,39	97,97	12,84	110,81
280	2js88JN$5FR85qHZtkOQha	92,46	1,00	25,56	5,00	1,39	92,46	18,40	110,86
5	3motmkzpH8EQg_TB5AF4fo	97,47	1,00	18,71	5,00	1,39	97,47	13,47	110,94
93	1ffb6CP750883SLaNor6tF	97,47	1,00	18,73	5,00	1,39	97,47	13,48	110,95
279	2js88JN$5FR85qHZtkOQhb	93,28	1,00	25,56	5,00	1,39	93,28	18,40	111,68
278	2js88JN$5FR85qHZtkOQhQ	93,49	1,00	25,56	5,00	1,39	93,49	18,40	111,89
277	2js88JN$5FR85qHZtkOQa4	99,39	1,00	25,56	5,00	1,39	99,39	18,40	117,79
283	2js88JN$5FR85qHZtkOQgr	99,68	1,00	25,56	5,00	1,39	99,68	18,40	118,08
276	2js88JN$5FR85qHZtkOQa5	99,74	1,00	25,56	5,00	1,39	99,74	18,40	118,14
86	1ffb6CP750883SLaNor6o1	98,72	1,00	28,33	5,00	1,39	98,72	20,40	119,12
85	1ffb6CP750883SLaNor6oU	99,59	1,00	27,78	5,00	1,39	99,59	20,00	119,60
18	1PPpxfKJ55fgFsHUsj1F4V	101,17	1,00	27,78	5,00	1,39	101,17	20,00	121,17
94	1ffb6CP750883SLaNor6s3	101,17	1,00	27,78	5,00	1,39	101,17	20,00	121,17
19	1PPpxfKJ55fgFsHUsj1F09	100,85	1,00	28,33	5,00	1,39	100,85	20,40	121,25
95	1ffb6CP750883SLaNor6s2	100,85	1,00	28,33	5,00	1,39	100,85	20,40	121,25
107	1ffb6CP750883SLaNor6xT	83,40	1,00	54,08	5,00	1,39	83,40	38,94	122,34
105	1ffb6CP750883SLaNor6xR	87,44	1,00	48,89	5,00	1,39	87,44	35,20	122,64
106	1ffb6CP750883SLaNor6xQ	87,45	1,00	48,96	5,00	1,39	87,45	35,25	122,70
108	1ffb6CP750883SLaNor6xS	83,12	1,00	55,03	5,00	1,39	83,12	39,62	122,74

104	1ffb6CP750883SLaNor6xO	87,69	1,00	48,88	5,00	1,39	87,69	35,19	122,89
109	1ffb6CP750883SLaNor6xV	83,24	1,00	55,55	5,00	1,39	83,24	40,00	123,23
91	1ffb6CP750883SLaNor6o4	92,62	1,00	43,05	5,00	1,39	92,62	31,00	123,62
129	1ffb6CP750883SLaNor6vX	84,02	1,00	55,03	5,00	1,39	84,02	39,62	123,64
110	1ffb6CP750883SLaNor6xU	83,73	1,00	55,57	5,00	1,39	83,73	40,01	123,74
24	1PPpxfKJ55fgFsHUsj10VZ	93,05	1,00	43,05	5,00	1,39	93,05	31,00	124,04
100	1ffb6CP750883SLaNor6s9	93,05	1,00	43,05	5,00	1,39	93,05	31,00	124,04
130	1ffb6CP750883SLaNor6vW	84,18	1,00	55,55	5,00	1,39	84,18	40,00	124,18
102	1ffb6CP750883SLaNor6xM	90,14	1,00	47,29	5,00	1,39	90,14	34,05	124,19
111	1ffb6CP750883SLaNor6x1	84,17	1,00	55,72	5,00	1,39	84,17	40,12	124,29
131	1ffb6CP750883SLaNor6vZ	84,56	1,00	55,57	5,00	1,39	84,56	40,01	124,57
25	1PPpxfKJ55fgFsHUsj10Sv	92,46	1,00	44,76	5,00	1,39	92,46	32,23	124,68
101	1ffb6CP750883SLaNor6s8	92,46	1,00	44,76	5,00	1,39	92,46	32,23	124,68
92	1ffb6CP750883SLaNor6o7	92,53	1,00	44,76	5,00	1,39	92,53	32,23	124,76
103	1ffb6CP750883SLaNor6xP	90,03	1,00	48,33	5,00	1,39	90,03	34,80	124,83
26	2Q8dbWbgj70wnET2xTXWkO	92,08	1,00	47,29	5,00	1,39	92,08	34,05	126,13
117	1ffb6CP750883SLaNor6vr	92,08	1,00	47,29	5,00	1,39	92,08	34,05	126,13
27	2Q8dbWbgj70wnET2xTXWkP	91,68	1,00	48,33	5,00	1,39	91,68	34,80	126,47
118	1ffb6CP750883SLaNor6vq	91,68	1,00	48,33	5,00	1,39	91,68	34,80	126,47
30	2Q8dbWbgj70wnET2xTXWkK	91,38	1,00	48,96	5,00	1,39	91,38	35,25	126,63
121	1ffb6CP750883SLaNor6vv	91,38	1,00	48,96	5,00	1,39	91,38	35,25	126,63
28	2Q8dbWbgj70wnET2xTXWkQ	91,53	1,00	48,88	5,00	1,39	91,53	35,19	126,73
119	1ffb6CP750883SLaNor6vt	91,53	1,00	48,88	5,00	1,39	91,53	35,19	126,73
112	1ffb6CP750883SLaNor6x0	83,43	1,00	61,19	5,00	1,39	83,43	44,06	127,48
35	2Q8dbWbgj70wnET2xTXWik	87,51	1,00	55,72	5,00	1,39	87,51	40,12	127,62
126	1ffb6CP750883SLaNor6vy	87,51	1,00	55,72	5,00	1,39	87,51	40,12	127,62
87	1ffb6CP750883SLaNor6o0	97,89	1,00	41,31	5,00	1,39	97,89	29,74	127,63
34	2Q8dbWbgj70wnET2xTXWij	87,70	1,00	55,57	5,00	1,39	87,70	40,01	127,72
125	1ffb6CP750883SLaNor6vz	87,70	1,00	55,57	5,00	1,39	87,70	40,01	127,72
113	1ffb6CP750883SLaNor6x3	83,16	1,00	62,20	5,00	1,39	83,16	44,78	127,95
88	1ffb6CP750883SLaNor6o3	97,68	1,00	42,24	5,00	1,39	97,68	30,41	128,10
114	1ffb6CP750883SLaNor6x2	83,66	1,00	62,39	5,00	1,39	83,66	44,92	128,58
89	1ffb6CP750883SLaNor6o2	97,74	1,00	43,20	5,00	1,39	97,74	31,10	128,85
36	2Q8dbWbgj70wnET2xTXWil	84,85	1,00	61,19	5,00	1,39	84,85	44,06	128,91
127	1ffb6CP750883SLaNor6v$	84,85	1,00	61,19	5,00	1,39	84,85	44,06	128,91
115	1ffb6CP750883SLaNor6x5	83,69	1,00	62,82	5,00	1,39	83,69	45,23	128,92
38	2Q8dbWbgj70wnET2xTXWif	84,02	1,00	62,39	5,00	1,39	84,02	44,92	128,95
29	2Q8dbWbgj70wnET2xTXWkR	93,80	1,00	48,89	5,00	1,39	93,80	35,20	129,00
120	1ffb6CP750883SLaNor6vs	93,80	1,00	48,89	5,00	1,39	93,80	35,20	129,00
20	1PPpxfKJ55fgFsHUsj10cl	99,36	1,00	41,31	5,00	1,39	99,36	29,74	129,10
96	1ffb6CP750883SLaNor6s5	99,36	1,00	41,31	5,00	1,39	99,36	29,74	129,10
37	2Q8dbWbgj70wnET2xTXWie	84,44	1,00	62,20	5,00	1,39	84,44	44,78	129,22
128	1ffb6CP750883SLaNor6v_	84,44	1,00	62,20	5,00	1,39	84,44	44,78	129,22
90	1ffb6CP750883SLaNor6o5	98,14	1,00	43,25	5,00	1,39	98,14	31,14	129,29

39	2Q8dbWbgj70wnET2xTXWig	84,18	1,00	62,82	5,00	1,39	84,18	45,23	129,41
116	1ffb6CP750883SLaNor6x4	84,10	1,00	63,02	5,00	1,39	84,10	45,37	129,48
40	2Q8dbWbgj70wnET2xTXWjW	84,56	1,00	63,02	5,00	1,39	84,56	45,37	129,93
31	2Q8dbWbgj70wnET2xTXWkL	91,08	1,00	54,08	5,00	1,39	91,08	38,94	130,02
122	1ffb6CP750883SLaNor6vu	91,08	1,00	54,08	5,00	1,39	91,08	38,94	130,02
32	2Q8dbWbgj70wnET2xTXWkM	90,50	1,00	55,03	5,00	1,39	90,50	39,62	130,12
123	1ffb6CP750883SLaNor6vx	90,50	1,00	55,03	5,00	1,39	90,50	39,62	130,12
21	1PPpxfKJ55fgFsHUsj10bt	99,71	1,00	42,24	5,00	1,39	99,71	30,41	130,12
97	1ffb6CP750883SLaNor6s4	99,71	1,00	42,24	5,00	1,39	99,71	30,41	130,12
33	2Q8dbWbgj70wnET2xTXWii	90,25	1,00	55,55	5,00	1,39	90,25	40,00	130,25
124	1ffb6CP750883SLaNor6vw	90,25	1,00	55,55	5,00	1,39	90,25	40,00	130,25
22	1PPpxfKJ55fgFsHUsj10bR	100,34	1,00	43,20	5,00	1,39	100,34	31,10	131,44
98	1ffb6CP750883SLaNor6s7	100,34	1,00	43,20	5,00	1,39	100,34	31,10	131,44
23	1PPpxfKJ55fgFsHUsj10aW	101,12	1,00	43,25	5,00	1,39	101,12	31,14	132,26
99	1ffb6CP750883SLaNor6s6	101,12	1,00	43,25	5,00	1,39	101,12	31,14	132,26
150	1ffb6CP750883SLaNor6_E	83,46	1,00	70,23	5,00	1,39	83,46	50,57	134,02
151	1ffb6CP750883SLaNor6_n	83,46	1,00	70,23	5,00	1,39	83,46	50,57	134,02
152	1ffb6CP750883SLaNor6_m	84,10	1,00	69,92	5,00	1,39	84,10	50,34	134,45
235	1lw7YFAH9EK9AqPA5fd9rg	10,07	1,00	174,32	5,00	1,39	10,07	125,51	135,58
248	37wGNYMZb9mB2SjWfJqJd2	10,07	1,00	174,32	5,00	1,39	10,07	125,51	135,58
232	1lw7YFAH9EK9AqPA5fd9rf	10,39	1,00	174,32	5,00	1,39	10,39	125,51	135,90
233	1lw7YFAH9EK9AqPA5fd9re	10,39	1,00	174,32	5,00	1,39	10,39	125,51	135,90
234	1lw7YFAH9EK9AqPA5fd9rh	10,39	1,00	174,32	5,00	1,39	10,39	125,51	135,90
247	37wGNYMZb9mB2SjWfJqJd1	10,39	1,00	174,32	5,00	1,39	10,39	125,51	135,90
15	1k9n0KaAr6A8uYKOaieQjx	16,10	1,00	174,32	5,00	1,39	16,10	125,51	141,61
82	0pDewtb85F39AGr4xd$rjc	91,81	1,00	70,23	5,00	1,39	91,81	50,57	142,38
171	1ffb6CP750883SLaNor6Zy	91,81	1,00	70,23	5,00	1,39	91,81	50,57	142,38
83	0pDewtb85F39AGr4xd$rkw	92,07	1,00	70,23	5,00	1,39	92,07	50,57	142,64
172	1ffb6CP750883SLaNor6Z$	92,07	1,00	70,23	5,00	1,39	92,07	50,57	142,64
81	0pDewtb85F39AGr4xd$rio	91,91	1,00	70,84	5,00	1,39	91,91	51,00	142,91
170	1ffb6CP750883SLaNor6Zz	91,91	1,00	70,84	5,00	1,39	91,91	51,00	142,91
84	0pDewtb85F39AGr4xd$rkF	92,69	1,00	69,92	5,00	1,39	92,69	50,34	143,04
173	1ffb6CP750883SLaNor6Z_	92,69	1,00	69,92	5,00	1,39	92,69	50,34	143,04
80	0pDewtb85F39AGr4xd$rip	92,27	1,00	71,62	5,00	1,39	92,27	51,57	143,83
169	1ffb6CP750883SLaNor6Zw	92,27	1,00	71,62	5,00	1,39	92,27	51,57	143,83
79	0pDewtb85F39AGr4xd$rhe	93,51	1,00	73,94	5,00	1,39	93,51	53,24	146,75
168	1ffb6CP750883SLaNor6Zx	93,51	1,00	73,94	5,00	1,39	93,51	53,24	146,75
78	0pDewtb85F39AGr4xd$rhf	93,71	1,00	77,35	5,00	1,39	93,71	55,69	149,40
167	1ffb6CP750883SLaNor6Zu	93,71	1,00	77,35	5,00	1,39	93,71	55,69	149,40
149	1ffb6CP750883SLaNor6_F	98,55	1,00	70,84	5,00	1,39	98,55	51,00	149,55
148	1ffb6CP750883SLaNor6_C	98,55	1,00	71,62	5,00	1,39	98,55	51,57	150,11
77	0pDewtb85F39AGr4xd$rhg	94,88	1,00	78,10	5,00	1,39	94,88	56,23	151,11
166	1ffb6CP750883SLaNor6Zv	94,88	1,00	78,10	5,00	1,39	94,88	56,23	151,11
147	1ffb6CP750883SLaNor6_D	98,55	1,00	73,94	5,00	1,39	98,55	53,24	151,79
146	1ffb6CP750883SLaNor6_A	98,55	1,00	77,35	5,00	1,39	98,55	55,69	154,24

145	1ffb6CP750883SLaNor6_B	98,47	1,00	78,10	5,00	1,39	98,47	56,23	154,70
272	2js88JN$5FR85qHZtkOQbv	100,62	1,00	78,18	5,00	1,39	100,62	56,29	156,91
273	2js88JN$5FR85qHZtkOQbu	100,79	1,00	78,18	5,00	1,39	100,79	56,29	157,08
271	2js88JN$5FR85qHZtkOQb_	100,93	1,00	78,18	5,00	1,39	100,93	56,29	157,22
275	2js88JN$5FR85qHZtkOQbw	106,56	1,00	85,64	5,00	1,39	106,56	61,66	168,23
274	2js88JN$5FR85qHZtkOQbx	106,82	1,00	85,64	5,00	1,39	106,82	61,66	168,48
267	2js88JN$5FR85qHZtkOQcK	108,16	1,00	85,64	5,00	1,39	108,16	61,66	169,82
69	0pDewtb85F39AGr4xd$rfo	153,49	1,00	85,90	5,00	1,39	153,49	61,85	215,34
158	1ffb6CP750883SLaNor6Zn	153,49	1,00	85,90	5,00	1,39	153,49	61,85	215,34
70	0pDewtb85F39AGr4xd$rgg	153,70	1,00	85,67	5,00	1,39	153,70	61,68	215,38
159	1ffb6CP750883SLaNor6Zm	153,70	1,00	85,67	5,00	1,39	153,70	61,68	215,38
74	0pDewtb85F39AGr4xd$rgc	157,39	1,00	80,96	5,00	1,39	157,39	58,29	215,68
163	1ffb6CP750883SLaNor6Zq	157,39	1,00	80,96	5,00	1,39	157,39	58,29	215,68
246	37wGNYMZb9mB2SjWfJqJd0	90,24	1,00	174,32	5,00	1,39	90,24	125,51	215,75
71	0pDewtb85F39AGr4xd$rgf	154,64	1,00	85,64	5,00	1,39	154,64	61,66	216,30
160	1ffb6CP750883SLaNor6Zp	154,64	1,00	85,64	5,00	1,39	154,64	61,66	216,30
72	0pDewtb85F39AGr4xd$rge	155,67	1,00	85,15	5,00	1,39	155,67	61,31	216,98
161	1ffb6CP750883SLaNor6Zo	155,67	1,00	85,15	5,00	1,39	155,67	61,31	216,98
9	09ItB_1cXCPAklRwfKv$5H	155,44	1,00	85,64	5,00	1,39	155,44	61,66	217,11
245	37wGNYMZb9mB2SjWfJqJdV	91,63	1,00	174,32	5,00	1,39	91,63	125,51	217,14
73	0pDewtb85F39AGr4xd$rgd	156,78	1,00	84,28	5,00	1,39	156,78	60,68	217,47
162	1ffb6CP750883SLaNor6Zr	156,78	1,00	84,28	5,00	1,39	156,78	60,68	217,47
216	0AMLC3KJP8eef1KJuhmSLJ	144,46	1,00	101,43	5,00	1,39	144,46	73,03	217,48
217	0AMLC3KJP8eef1KJuhmSLG	145,15	1,00	100,64	5,00	1,39	145,15	72,46	217,61
68	0pDewtb85F39AGr4xd$rfp	152,40	1,00	91,25	5,00	1,39	152,40	65,70	218,09
157	1ffb6CP750883SLaNor6ZE	152,40	1,00	91,25	5,00	1,39	152,40	65,70	218,09
218	0AMLC3KJP8eef1KJuhmSLH	146,22	1,00	100,10	5,00	1,39	146,22	72,07	218,29
259	37wGNYMZb9mB2SjWfJqJZS	93,00	1,00	174,32	5,00	1,39	93,00	125,51	218,51
65	0pDewtb85F39AGr4xd$rfs	152,47	1,00	92,64	5,00	1,39	152,47	66,70	219,17
154	1ffb6CP750883SLaNor6ZD	152,47	1,00	92,64	5,00	1,39	152,47	66,70	219,17
62	2Q8dbWbgj70wnET2xTXW_h	147,46	1,00	99,67	5,00	1,39	147,46	71,76	219,22
219	0AMLC3KJP8eef1KJuhmSKk	147,46	1,00	99,67	5,00	1,39	147,46	71,76	219,22
67	0pDewtb85F39AGr4xd$rfq	153,06	1,00	92,10	5,00	1,39	153,06	66,32	219,38
156	1ffb6CP750883SLaNor6ZF	153,06	1,00	92,10	5,00	1,39	153,06	66,32	219,38
64	0pDewtb85F39AGr4xd$rdF	152,58	1,00	92,88	5,00	1,39	152,58	66,87	219,45
153	1ffb6CP750883SLaNor6ZA	152,58	1,00	92,88	5,00	1,39	152,58	66,87	219,45
63	2Q8dbWbgj70wnET2xTXW_a	148,49	1,00	98,80	5,00	1,39	148,49	71,14	219,62
220	0AMLC3KJP8eef1KJuhmSKl	148,49	1,00	98,80	5,00	1,39	148,49	71,14	219,62
258	37wGNYMZb9mB2SjWfJqJZR	94,39	1,00	174,32	5,00	1,39	94,39	125,51	219,90
66	0pDewtb85F39AGr4xd$rfr	153,60	1,00	92,62	5,00	1,39	153,60	66,69	220,28
155	1ffb6CP750883SLaNor6ZC	153,60	1,00	92,62	5,00	1,39	153,60	66,69	220,28
76	0pDewtb85F39AGr4xd$rhh	164,70	1,00	78,18	5,00	1,39	164,70	56,29	220,99
165	1ffb6CP750883SLaNor6Zs	164,70	1,00	78,18	5,00	1,39	164,70	56,29	220,99

75	0pDewtb85F39AGr4xd$rhi	164,63	1,00	78,29	5,00	1,39	164,63	56,37	221,00
164	1ffb6CP750883SLaNor6Zt	164,63	1,00	78,29	5,00	1,39	164,63	56,37	221,00
260	37wGNYMZb9mB2SjWfJqJZT	95,79	1,00	174,32	5,00	1,39	95,79	125,51	221,30
10	09ItB_1cXCPAklRwfKv$5h	159,68	1,00	85,64	5,00	1,39	159,68	61,66	221,34
211	0AMLC3KJP8eef1KJuhmSLM	143,80	1,00	109,90	5,00	1,39	143,80	79,13	222,92
212	0AMLC3KJP8eef1KJuhmSLN	143,56	1,00	110,64	5,00	1,39	143,56	79,66	223,22
213	0AMLC3KJP8eef1KJuhmSLK	143,02	1,00	111,77	5,00	1,39	143,02	80,48	223,49
215	0AMLC3KJP8eef1KJuhmSLI	143,41	1,00	111,60	5,00	1,39	143,41	80,35	223,76
214	0AMLC3KJP8eef1KJuhmSLL	143,14	1,00	112,01	5,00	1,39	143,14	80,64	223,79
209	0AMLC3KJP8eef1KJuhmSLO	145,22	1,00	114,58	5,00	1,39	145,22	82,50	227,72
210	0AMLC3KJP8eef1KJuhmSLP	145,31	1,00	114,58	5,00	1,39	145,31	82,50	227,81
208	0AMLC3KJP8eef1KJuhmSLR	146,09	1,00	114,58	5,00	1,39	146,09	82,50	228,58
207	0AMLC3KJP8eef1KJuhmSLQ	146,42	1,00	114,89	5,00	1,39	146,42	82,72	229,14
59	2Q8dbWbgj70wnET2xTXW_e	160,06	1,00	101,43	5,00	1,39	160,06	73,03	233,09
266	2js88JN$5FR85qHZtkOQcL	107,87	1,00	174,32	5,00	1,39	107,87	125,51	233,38
61	2Q8dbWbgj70wnET2xTXW_g	161,42	1,00	100,10	5,00	1,39	161,42	72,07	233,49
60	2Q8dbWbgj70wnET2xTXW_f	161,03	1,00	100,64	5,00	1,39	161,03	72,46	233,49
265	2js88JN$5FR85qHZtkOQcA	108,14	1,00	174,32	5,00	1,39	108,14	125,51	233,65
54	2Q8dbWbgj70wnET2xTXWvJ	158,54	1,00	109,87	5,00	1,39	158,54	79,10	237,65
55	2Q8dbWbgj70wnET2xTXW_i	158,31	1,00	111,17	5,00	1,39	158,31	80,04	238,35
57	2Q8dbWbgj70wnET2xTXW_k	157,97	1,00	112,01	5,00	1,39	157,97	80,64	238,62
58	2Q8dbWbgj70wnET2xTXW_l	158,31	1,00	111,59	5,00	1,39	158,31	80,34	238,65
56	2Q8dbWbgj70wnET2xTXW_j	158,28	1,00	111,86	5,00	1,39	158,28	80,54	238,82
264	2js88JN$5FR85qHZtkOQcB	113,91	1,00	174,32	5,00	1,39	113,91	125,51	239,42
263	2js88JN$5FR85qHZtkOQc8	114,06	1,00	174,32	5,00	1,39	114,06	125,51	239,57
239	1lw7YFAH9EK9AqPA5fd9wV	115,01	1,00	174,32	5,00	1,39	115,01	125,51	240,52
268	2js88JN$5FR85qHZtkOQcN	115,01	1,00	174,32	5,00	1,39	115,01	125,51	240,52
240	1lw7YFAH9EK9AqPA5fd9wU	115,09	1,00	174,32	5,00	1,39	115,09	125,51	240,60
269	2js88JN$5FR85qHZtkOQcM	115,09	1,00	174,32	5,00	1,39	115,09	125,51	240,60
270	2js88JN$5FR85qHZtkOQcH	115,63	1,00	174,32	5,00	1,39	115,63	125,51	241,14
206	0AMLC3KJP8eef1KJuhmSLT	158,42	1,00	115,54	5,00	1,39	158,42	83,19	241,61
52	2Q8dbWbgj70wnET2xTXWvH	159,81	1,00	114,58	5,00	1,39	159,81	82,50	242,31
53	2Q8dbWbgj70wnET2xTXWvI	160,09	1,00	114,53	5,00	1,39	160,09	82,46	242,55
142	1ffb6CP750883SLaNor6_6	184,86	1,00	80,96	5,00	1,39	184,86	58,29	243,15
51	2Q8dbWbgj70wnET2xTXWvG	160,73	1,00	114,58	5,00	1,39	160,73	82,50	243,23
194	0AMLC3KJP8eef1KJuhmSOE	170,82	1,00	100,64	5,00	1,39	170,82	72,46	243,28

328	14I4MIpV12xxTvWqZvAdHY	118,73	1,00	173,19	5,00	1,39	118,73	124,70	243,43
195	0AMLC3KJP8eef1KJuhmSOF	171,43	1,00	100,10	5,00	1,39	171,43	72,07	243,50
133	1ffb6CP750883SLaNor6_V	176,86	1,00	92,64	5,00	1,39	176,86	66,70	243,56
193	0AMLC3KJP8eef1KJuhmSOn	170,56	1,00	101,43	5,00	1,39	170,56	73,03	243,59
132	1ffb6CP750883SLaNor6_S	177,14	1,00	92,88	5,00	1,39	177,14	66,87	244,01
196	0AMLC3KJP8eef1KJuhmSOC	172,28	1,00	99,67	5,00	1,39	172,28	71,76	244,03
205	0AMLC3KJP8eef1KJuhmSLS	158,42	1,00	118,91	5,00	1,39	158,42	85,62	244,04
134	1ffb6CP750883SLaNor6_U	177,56	1,00	92,62	5,00	1,39	177,56	66,69	244,25
143	1ffb6CP750883SLaNor6_9	187,88	1,00	78,29	5,00	1,39	187,88	56,37	244,25
197	0AMLC3KJP8eef1KJuhmSOD	173,14	1,00	98,80	5,00	1,39	173,14	71,14	244,28
144	1ffb6CP750883SLaNor6_8	188,10	1,00	78,18	5,00	1,39	188,10	56,29	244,39
50	2Q8dbWbgj70wnET2xTXWvN	161,77	1,00	114,86	5,00	1,39	161,77	82,70	244,47
141	1ffb6CP750883SLaNor6_7	184,48	1,00	84,28	5,00	1,39	184,48	60,68	245,16
140	1ffb6CP750883SLaNor6_4	183,96	1,00	85,15	5,00	1,39	183,96	61,31	245,26
335	14I4MIpV12xxTvWqZvAdGc	119,84	1,00	174,32	5,00	1,39	119,84	125,51	245,35
329	14I4MIpV12xxTvWqZvAdHX	119,84	1,00	174,32	5,00	1,39	119,84	125,51	245,35
139	1ffb6CP750883SLaNor6_5	183,79	1,00	85,64	5,00	1,39	183,79	61,66	245,45
327	14I4MIpV12xxTvWqZvAdHZ	120,29	1,00	173,97	5,00	1,39	120,29	125,26	245,55
138	1ffb6CP750883SLaNor6_2	184,19	1,00	85,67	5,00	1,39	184,19	61,68	245,87
49	2Q8dbWbgj70wnET2xTXWvM	162,90	1,00	115,51	5,00	1,39	162,90	83,17	246,07
204	0AMLC3KJP8eef1KJuhmSLV	158,22	1,00	122,23	5,00	1,39	158,22	88,00	246,23
310	14I4MIpV12xxTvWqZvAdTV	127,33	1,00	165,15	5,00	1,39	127,33	118,91	246,23
136	1ffb6CP750883SLaNor6_0	180,54	1,00	91,25	5,00	1,39	180,54	65,70	246,24
203	0AMLC3KJP8eef1KJuhmSLU	157,95	1,00	122,66	5,00	1,39	157,95	88,31	246,27
202	0AMLC3KJP8eef1KJuhmSL1	158,03	1,00	122,66	5,00	1,39	158,03	88,31	246,34
137	1ffb6CP750883SLaNor6_3	184,61	1,00	85,90	5,00	1,39	184,61	61,85	246,46
201	0AMLC3KJP8eef1KJuhmSL0	158,16	1,00	122,75	5,00	1,39	158,16	88,38	246,54
321	14I4MIpV12xxTvWqZvAdUv	121,03	1,00	174,32	5,00	1,39	121,03	125,51	246,54
135	1ffb6CP750883SLaNor6_1	180,24	1,00	92,10	5,00	1,39	180,24	66,32	246,55
324	14I4MIpV12xxTvWqZvAdH_	121,32	1,00	174,32	5,00	1,39	121,32	125,51	246,83
332	14I4MIpV12xxTvWqZvAdGX	121,33	1,00	174,32	5,00	1,39	121,33	125,51	246,84
325	14I4MIpV12xxTvWqZvAdHz	121,67	1,00	173,97	5,00	1,39	121,67	125,26	246,92
326	14I4MIpV12xxTvWqZvAdHy	122,25	1,00	173,19	5,00	1,39	122,25	124,70	246,95
188	0AMLC3KJP8eef1KJuhmSOq	168,01	1,00	109,84	5,00	1,39	168,01	79,09	247,10
331	14I4MIpV12xxTvWqZvAdGY	121,68	1,00	174,32	5,00	1,39	121,68	125,51	247,19
318	14I4MIpV12xxTvWqZvAdUq	123,07	1,00	172,45	5,00	1,39	123,07	124,16	247,23
200	0AMLC3KJP8eef1KJuhmSL3	158,41	1,00	123,38	5,00	1,39	158,41	88,83	247,24
322	14I4MIpV12xxTvWqZvAdUu	122,22	1,00	173,87	5,00	1,39	122,22	125,19	247,41

319	14I4MIpV12xxTvWqZvAdUx	124,04	1,00	171,74	5,00	1,39	124,04	123,65	247,69
330	14I4MIpV12xxTvWqZvAdGZ	122,31	1,00	174,32	5,00	1,39	122,31	125,51	247,82
323	14I4MIpV12xxTvWqZvAdU$	123,60	1,00	172,56	5,00	1,39	123,60	124,25	247,85
320	14I4MIpV12xxTvWqZvAdUw	125,12	1,00	170,51	5,00	1,39	125,12	122,77	247,88
189	0AMLC3KJP8eef1KJuhmSOr	168,03	1,00	111,21	5,00	1,39	168,03	80,07	248,11
314	14I4MIpV12xxTvWqZvAdT3	124,98	1,00	171,27	5,00	1,39	124,98	123,31	248,29
315	14I4MIpV12xxTvWqZvAdT2	126,36	1,00	169,88	5,00	1,39	126,36	122,31	248,67
316	14I4MIpV12xxTvWqZvAdT1	127,74	1,00	168,13	5,00	1,39	127,74	121,05	248,79
48	2Q8dbWbgj70wnET2xTXWvL	163,47	1,00	118,92	5,00	1,39	163,47	85,62	249,09
190	0AMLC3KJP8eef1KJuhmSOo	168,62	1,00	111,94	5,00	1,39	168,62	80,60	249,22
191	0AMLC3KJP8eef1KJuhmSOp	168,73	1,00	112,01	5,00	1,39	168,73	80,64	249,37
311	14I4MIpV12xxTvWqZvAdTU	128,25	1,00	168,36	5,00	1,39	128,25	121,22	249,47
312	14I4MIpV12xxTvWqZvAdTT	129,30	1,00	167,07	5,00	1,39	129,30	120,29	249,59
16	1k9n0KaAr6A8uYKOaieQkj	117,94	1,00	183,15	5,00	1,39	117,94	131,87	249,80
192	0AMLC3KJP8eef1KJuhmSOm	169,80	1,00	111,58	5,00	1,39	169,80	80,34	250,14
317	14I4MIpV12xxTvWqZvAdT0	129,21	1,00	168,76	5,00	1,39	129,21	121,51	250,72
313	14I4MIpV12xxTvWqZvAdTS	130,42	1,00	167,27	5,00	1,39	130,42	120,44	250,86
187	0AMLC3KJP8eef1KJuhmSOt	170,72	1,00	114,45	5,00	1,39	170,72	82,40	253,12
186	0AMLC3KJP8eef1KJuhmSOs	170,76	1,00	114,58	5,00	1,39	170,76	82,50	253,26
185	0AMLC3KJP8eef1KJuhmSOv	171,13	1,00	114,58	5,00	1,39	171,13	82,50	253,63
199	0AMLC3KJP8eef1KJuhmSL2	159,28	1,00	131,54	5,00	1,39	159,28	94,71	253,99
333	14I4MIpV12xxTvWqZvAdGW	128,74	1,00	174,32	5,00	1,39	128,74	125,51	254,25
334	14I4MIpV12xxTvWqZvAdGd	128,74	1,00	174,32	5,00	1,39	128,74	125,51	254,25
184	0AMLC3KJP8eef1KJuhmSOu	171,81	1,00	114,83	5,00	1,39	171,81	82,68	254,49
198	0AMLC3KJP8eef1KJuhmSL5	160,16	1,00	131,69	5,00	1,39	160,16	94,82	254,97
6	1S$XS4sLb7ie56ea0OapsB	149,53	1,00	146,99	5,00	1,39	149,53	105,83	255,36
17	1k9n0KaAr6A8uYKOaieQWq	124,61	1,00	182,49	5,00	1,39	124,61	131,39	256,00
336	3NcD8Lk2TDweKVDkCkBfUm	129,30	1,00	179,99	5,00	1,39	129,30	129,59	258,90
337	3NcD8Lk2TDweKVDkCkBfVN	129,30	1,00	180,01	5,00	1,39	129,30	129,61	258,91
174	0AMLC3KJP8eef1KJuhmSPW	156,67	1,00	143,01	5,00	1,39	156,67	102,97	259,63
47	2Q8dbWbgj70wnET2xTXWvK	172,91	1,00	122,27	5,00	1,39	172,91	88,04	260,95
46	2Q8dbWbgj70wnET2xTXWvR	172,67	1,00	122,66	5,00	1,39	172,67	88,31	260,98
45	2Q8dbWbgj70wnET2xTXWvQ	172,91	1,00	122,66	5,00	1,39	172,91	88,31	261,22
44	2Q8dbWbgj70wnET2xTXWvP	172,88	1,00	122,81	5,00	1,39	172,88	88,43	261,30
183	0AMLC3KJP8eef1KJuhmSOx	172,71	1,00	123,51	5,00	1,39	172,71	88,92	261,63
43	2Q8dbWbgj70wnET2xTXWvO	173,14	1,00	123,44	5,00	1,39	173,14	88,88	262,02

7	1S$XS4sLb7ie56ea0Oao1V	157,70	1,00	146,10	5,00	1,39	157,70	105,19	262,90
180	0AMLC3KJP8eef1KJuhmS Oy	176,08	1,00	122,66	5,00	1,39	176,08	88,31	264,39
182	0AMLC3KJP8eef1KJuhmS Ow	173,21	1,00	131,70	5,00	1,39	173,21	94,83	268,03
241	1lw7YFAH9EK9AqPA5fd9x L	142,65	1,00	174,32	5,00	1,39	142,65	125,51	268,16
181	0AMLC3KJP8eef1KJuhmS Oz	175,51	1,00	129,82	5,00	1,39	175,51	93,47	268,98
41	2Q8dbWbgj70wnET2xTXW vU	175,93	1,00	129,78	5,00	1,39	175,93	93,44	269,37
42	2Q8dbWbgj70wnET2xTXW vV	176,26	1,00	131,62	5,00	1,39	176,26	94,77	271,03
179	0AMLC3KJP8eef1KJuhmS O$	183,24	1,00	122,66	5,00	1,39	183,24	88,31	271,55
178	0AMLC3KJP8eef1KJuhmS O_	183,29	1,00	122,87	5,00	1,39	183,29	88,47	271,76
177	0AMLC3KJP8eef1KJuhmS OX	183,60	1,00	123,51	5,00	1,39	183,60	88,92	272,52
4	1oXs4mReX9Sw6ofBBrrsl4	171,40	1,00	142,98	5,00	1,39	171,40	102,94	274,34
175	0AMLC3KJP8eef1KJuhmS OZ	185,78	1,00	129,82	5,00	1,39	185,78	93,47	279,25
176	0AMLC3KJP8eef1KJuhmS OW	184,74	1,00	131,70	5,00	1,39	184,74	94,83	279,57
0	0WrIc5W$z589skXkTKCW XM	180,68	1,00	142,94	5,00	1,39	180,68	102,92	283,60

FIGURE 45. TIMESHEET OF ANALYSIS OF COVERED PATHS, ORDERED BY DECREASING COMBINED SPEED

The “Combiner of Multi-Target Partial Plans” layer then, uses an approach similar to the “Ant Colony” [82] to link the partial paths to the intermediate points. Firstly, the intermediate windows not connected internally and externally are excluded and so the incomplete paths are discarded. Considering the same example, for each window through which exists an alternative way out, the total escape time and the coordinates of the intermediate window can be deduced and compared to the ones belonging to other windows. The “Most Promising Executable Plan” corresponds to the shortest complete path to exit the building, i.e. in the shortest possible time.

Total number of windows	344
Number of windows reachable by the user	343
Number of windows reachable by the rescue team	337

FIGURE 46. PLOT OF RESULTED REACHABLE WINDOWS

By combining the results of the points reachable by both the Rescue Team and the users, with the time employed to cover the paths to reach them, it has been possible to extract the set of possible multitarget plans to execute, concretizing the hypothesized collaboration among holons.

The system has therefore, shown its capabilities of acquiring information about the environment’s status and finding alternative solutions in case of unexpected events, employing a reduced time and a poor computing effort. Alternative solutions are found in a time extremely lower that the one that rescue parties would take in the activities of physical evaluation of the system’s criticalities on site and search for alternative solution, presenting itself as a useful tool in assistance to rescue operations, that for the character of emergency, must be time-constrained and efficient.

CHAPTER 6

Conclusions and Future Developments

6.1 CONCLUSIONS

This dissertation has reported the research activities carried out by the author with the support of the relative Department Research Group, towards the investigation of a novel approach in the Building Emergency Management, considered as a topic of increasing interest in nowadays lives and in scientific research.

Beginning from the analysis of several approaches to the matter, from the normative standards to the most recent scientific studies, the research has found its objective in the overcoming of the limits of the actual traditional approaches that, in our analysis, result affected by inefficient information and management workflows.

The main criticality in the actual approach has been found in a weak consideration of the possibility of the occurrence of unexpected events that in continuously evolving scenarios may happen, seriously compromising the success of the evacuation and rescue operations, with catastrophic consequences, as in the examples reported in chapter 1.

Therefore, the main encountered limits have been precisely defined, in order to find specific improvement methods to tackle them, as summarized in the following.

- The inefficiency revealed in the **information flow** that relies on a bottom-up approach and is often demanded to static, not reliable and incomplete means, has been faced by the proposal of the extraction of information from general data that are commonly available and not always properly exploited. More precisely, the reasoning activity is triggered by the need of finding further information during an emergency scenario characterized by the occurrence of unexpected invalidating events. BIM models have been proposed as providers of topological information about the involved buildings, as well as a punctual automatic data collection about the environment has been proposed by the means of Internet Of Things emergent technologies. Moreover, a **semantic enhancement** has been proposed, enriching the meaning of the single BIM objects as unconventional means that can be utilized during emergencies. Finally, the data automatic collected by sensors deployed on site supply a continuously updated information flow about the environment's evolution and trapped people position, avoiding time consuming and dangerous activities of verification physically conducted on site.

- The emergency management workflow is usually characterized by a top-down approach relying on the aforementioned bottom-up information flow. This architecture is affected by a general lack of flexibility and a slowing down due to the need of reporting information to the highest level of the management hierarchy and a consequent descendant flow of decision making about the actions to be executed that may result no more effective when applied in an evolved scenario.

  To provide the emergency management workflow with the needed flexibility and adaptability to an always-changing environment, we have proposed to implement the holonic theory. It promotes a major autonomy of the lowest levels of the hierarchy in order to make them able to fulfil local objectives on their own as well as to cooperate in temporary subsystems (the "holarchies"), in order to face and solve common problems. Furthermore, another powerful mean widely diffused to face uncertainties, namely the Bayesian Networks, has been employed for a rapid and efficient selection of the most suitable set of unconventional solutions, on the basis of the involved resources' availability, as reported by single agents (the "ants") sent in search of alternative solutions.

  Through the application of these theories and means, we have retained that the system would be seriously improved with the necessary flexibility, resilience and adaptability.

The conceptualized topics have been embodied by a specifically developed system architecture, which foresees the employment of the following functional blocks:

- BIM models as provider of topological information;
- Simulation engines as provider of simulated data about sensors deployed on site and Bayesian Networks to select the most suitable plans among a set of unconventional ones;
- A virtual reality platform as collector of data deriving from BIM models and simulation engines, which allows implementing holons by the use of elements of Artificial Intelligence and conduct tests about the overall architecture.

The system has been applied to the case study of the mixed-use building of Eustachio (Faculty of Medicine of Ancona) in a fire emergency scenario in which several unexpected events have been simulated. The system has showed a great capability of resilience in the search for unconventional solutions, followed by the selection of the most suitable plans among a set of alternatives to the standard emergency operations, achieving the confirmation of our theoretical milestones.

6.2 FUTURE DEVELOPMENTS

The system has demonstrated to be reliable and effective in terms of fulfilling of theoretical principles and analysed data, opening the road for a promising novel approach that allows overcoming the limits of the traditional emergency management approach.

The developed system architecture may be utilized as an assistance tool for rescuers and evacuees that in reduced time and with a limited computing effort, enables the search of unconventional solutions to face unexpected events that affect the normal execution of standard operations, as foreseen by normative. The employment of commercial software for the building of the functional blocks composing the system architecture, promotes the diffusion of the tool, while the effectiveness and flexibility of the approach invocate the extension of the methodology to other emergency scenarios beside the fire one.

Alternative and more intuitive information means constituted by continuously updating BIM models shown on interactive panels could substitute the standard emergency plans, affected by a not clear and immediate understandability.

Finally, possible developments may involve a further integration of data coming from heterogeneous sources from new emerging technologies (e.g. real-time localization systems) as well as the application of the methodology to environments characterized by a higher level of complexity in terms of building features (e.g. big infrastructures), emergency causes and unexpected scenarios.

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