A simulation tool for crisis management and pre-disaster planning

Federico Eugeni, Sara Sacco, Donato Di Ludovico
Department of Civil, Construction-Architectural and Environmental Engineering
University of L'Aquila
L'Aquila, Italy
federico.eugeni@univaq.it, sara.sacco1@graduate.univaq.it, donato.diludovico@univaq.it

Antinisca Di Marco
Department of Information Engineering, Computer Science and Mathematics
University of L'Aquila
L'Aquila, Italy
antinisca.dimarco@univaq.it

***Abstract*—Natural and anthropic disasters can affect every city and urban area. Urbanists, engineers, and decision-makers must work towards reducing risks to the population in case a disaster occurs. This paper proposes a new methodology based on algorithmically calculated risk scenarios and on human behavioural simulation models that aims to evaluate and eventually improve crisis management and pre-disaster planning at the urban level The approach is based on GAMA, an agent-oriented simulation tool that allows the formulation of integrated models utilizing multiple modelling paradigms, the exploration of parameter space, the calibration of several models, and the performance of virtual experiments through the integration of vector and raster geographic data. The objective of the proposed methodology is to devise a platform that can be used to: i) validate, using simulation, the qualities of the urban structures and characteristics of city components concerning their capacity to respond to a catastrophic event, and ii) more importantly, to define new urban design strategies oriented toward safety with the final goal of improving the resilience of our cities. The article provides the preliminary findings from a case study on which the approach under development was applied.**

Keywords—simulation, agent-based programming, pre-disaster, planning, urban design

I. Introduction

One of the competencies of today's urban planners is the ability to proficiently shape a dynamic approach that deals with the challenges that today's society presents them. Such challenges require urban planners to devise novel methodologies and implement cutting-edge tools that can support urban planning practice. Given the occurrence of natural disasters [1], it is fundamental to identify the possible effects of such events in advance both for theoretical and academic reasons and most importantly, for practical aspects. Implementing sophisticated simulation frameworks helps to increase the degree of readiness and comprehension of society at all levels, aspects that are effective in portraying the reality around us. To prepare, communicate, and inform inhabitants, authorities, and players in the territories, independently of their previous disaster history, it is crucial a component that simulates the portrayal of possible arising conditions, behaviour, and risk scenarios. A comprehensive development necessitates new approaches that cannot merely be founded on considering recurrent historical events. In the sphere of events across Europe as well as around the world, the topic of catastrophic events modelling is often debated, but not in Italy. Although the cause of this is unclear, certain hypotheses can be made. Geographical pieces of information on urban reality, which are essential for doing studies and assessments of this nature, are not uniformly available across the nation. The physical configuration of the same, in both its natural and anthropogenic components (consider, for instance, the nearby mountainous regions and minor historical centres), involves several analytical challenges. These might be two of the causes of what seems to be disenchantment with the general topic of Disaster Risk Management.

Pre-disaster planning studies and practices today exhibit solid foundations since models and procedures have been developed based on the well-documented incidence of catastrophic occurrences on the national territory [2,3,16]. However, in this regard, today some more can be done with the help of innovative technologies in terms of prevention, risk reduction and timeliness. The research discussed in this paper deals with the creation of crowd motion simulation methods at an urban scale about the territorial paradigm and Urban Digital Twin technology [4,5,17], intending to bridge the gap between the two previous proposed issues (construction of the knowledge system and its use for evaluating the performance of the urban structure about disaster events) and serve as support and validation tool for pre-disaster planning.

In scientific literature, the topic of crowd behaviour simulation is confined to the study of simulation models about collective human dynamics. In this context, there are many studies aimed at simulating crowd behaviour during a disaster event, essentially focusing on the construction of algorithms, numerical analysis and tools for their application. Such studies use approaches based on multi-agent models that incorporate crowd panic behavior [19, 25], or leveraging on non-human model organisms or cellular automaton models [18, 19, 25].

The above research involves simulation inside buildings [19, 24] and simulation in urban environments [20, 21], crowd evacuations distributed simulators [20], also based on game and artificial intelligence technologies [21]. Instead, The disasters to which such simulations refer are very often related to seismic and fire hazards. The approaches use simulation platforms [22], including open-source platforms [11, 23, 24]. Our literature review on the topic of evacuation simulations has highlighted that studies focus heavily on algorithm definitions and the resulting simulation, However, it is missing works that build a complete model of an urban area, typically composed of geographical data, updated statistics (e.g., on population, mobility and so on) and real-time data collected from sensors (e.g., road traffic, population density in critical area, and so on), and that especially do not contextualize the simulation in the broader urbanist topic of pre-disaster planning. We aim to bridge these gaps with a multi-scalar and multi-disciplinary approach, structuring a platform, in the form of a Digital Twin, that embeds the *minimal* data required for urban analysis and uses simulation to structure pre-disaster planning practices and urban design techniques aimed at reducing risk and therefore increasing resilience. The scope of this paper is to define a novel platform that can be used to validate, using simulation, the qualities of urban structures and characteristics of city components concerning their capacity to respond to a catastrophic event. More importantly, it can be used to define new urban design strategies oriented toward safety with the final goal of improving the resilience of our cities. The article provides the preliminary findings from a case study on which the approach under development was applied.

The case study is situated in the first suburbs of the city of L'Aquila in Abruzzo which is currently finishing up the private building structures reconstruction that was started after the seismic events that happened in April 2009 [6]. The approach employed, as will be discussed later, is intended to confirm the ability to react to the eventual occurrences of a natural catastrophe (of seismic nature and beyond). By doing so, it will be feasible to develop innovative urban planning and design approaches that are focused on the resiliency of the city's inhabitants. As already experimented by Caillou [7] by testing simple approaches to agent-based modeled simulations using GIS data the techniques used for the research rely on analyzing tridimensional geographical data in agent-based modelling applications. Towards the compilation of a code that can perform a simulation of crowd motion at an urban scale, pieces of information that are currently accessible on the web through the geoportal of the Abruzzo Region, alongside pieces of information that are derived within the software itself, are employed.

While still in its early stages, this work incorporates some of the working team's actions into a larger scenario. Referring to the topic of new forms and instruments of urban and territorial planning that correspond to the demands of contemporaneity and the environments in which it shows itself and develops, mention is made to the development of Territorial Information Platforms [8]. Additionally, experiments involving the Digital Twin [9, 17] and City Information Modeling [10, 17] should be mentioned. These multifaceted systems of knowledge aim to create open, continually evolving models of three-dimensional visualizations of events occurring on an urban and territorial scale.

The paper proceeds as follows: in section II, we report about similar agent-based frameworks used to simulate scenarios in case of crisis management and pre-disaster planning; section III describes the methodology used that combines the usage of digital twin, the agent-based simulation tool (through GAMMA technology) and urban planning and design techniques to increase the resiliency of urban environments. Section IV reports preliminary promising results and, finally, Section V concludes the paper and sketches future work.

II. Reference Framework

There are various examples of using and experimenting with simulation tools on an urban level employing the concepts of agent-based modelling of dynamics in the literature worldwide. These are a group of computational models used to evaluate the impacts of self-identified individuals' behaviour and relationships on the system through digital simulation. Any component of a system whose behaviour can be specified, such as individuals, infrastructure, paths, traffic, etc., is referred to as an agent. Along with the review of the information available, software for simulation (both paid and open-source freely available) was thoroughly examined in terms of the scientific models they use (the majority employ agent-based simulation techniques), their 2D or 3D visualization capabilities, their use of graphs or grids for urban analysis and graphical representation of results, and the total amount of agents that can be employed. Gama Platform [11,12,13], a modelling and simulation development system for the creation of spatially detailed agent-based simulations, is the technology we select for our work. In GAMA, models are created using a Java-based programming language. and shapefiles that include georeferenced information can be imported and visualized to undertake studies at multiple spatial scales and levels of representation.

Other than GAMA, in literature there are other frameworks like GAMA such us ACTEUR [12], Cityscope [26] and Escape [14]. The ACTEUR project aims to develop a platform that helps modellers, in particular geographers and town planners, to design and calibrate through graphical language a cognitive agent capable of acting in a complex spatial environment. The platform also has the ambition to support model discussion - participatory modelling - between the different stakeholders (geographers, sociologists, urban planners, decision-makers, etc.). These tools are integrated into the GAMA platform, which allows users to build large-scale models with thousands of agents and has already been used to develop models with cognitive agents.

CityScope is a tangible and digital platform, developed at the MIT Media Lab, dedicated to solving the challenges of spatial design and urban planning through tools ranging from simulations that quantify the impact of design (physical and intangible) in cities to collaborative communication applications. Through CityScope, these tools are distributed globally through a network called 'CityScience', maintaining open-source databases for most implementations. In this context, GAMA was used to implement an agent-based simulation platform for research projects aimed at understanding behavioural patterns related to housing and mobility patterns in the design of urban policies.

Escape [14] aims to implement an operational research system on crowd evacuation at the urban scale. The project is based on the relationship between geographic information systems, multiscale modelling of ongoing phenomena at the urban scale and digitized simulation tools aimed at exploring these models. The system is implemented and validated on real case studies to generate realistic simulations to test evacuation strategies by state bodies dealing directly with emergencies. By combining sources such as spatial information (land use, transport networks, sprawl and hazards), and demographic data, with simulators for mobility and traffic management (cars, bicycles, pedestrians, public transport) it is capable of visualizing different evacuation strategies (partial or complete, wave or synchronous) and providing measures of evacuation times in different crisis zones.

We decided to base our methodology on GAMA since it is open source and allows for the usage of geospatial data spanning from two to three dimensions, thereby making it workable in a GIS system that is the exact standard used in traditional planning tools.

III. Methodology

The methodology proposed in this paper is composed of several closely interrelated elements. To construct innovative practices and theories of design and planning at different scales, the idea is to build a system, founded on solid cognitive foundations, capable of enhancing urban resilience and thus the capacity to respond to risks and, more generally, to the occurrence of natural disasters. The methodology applies new and innovative urban design techniques, the results of which will be cyclically controlled by specially designed and implemented simulation tools.

The methodology, as depicted in Fig. 1, is composed of five phases: (1) the construction of a knowledge system in the form of an Urban Digital Twin (UDT), (2) the selection of cross-scale case studies of the UDT on which to apply the output of phase 3, (3) the realization of a software application with agent-based programming techniques aimed at simulating evacuation during a disaster, (4) the definition of urban design techniques on the case studies for reducing risks during evacuation, and (5) the feedback application of phase 3 to verify the urban performance of the techniques defined in phase 4.

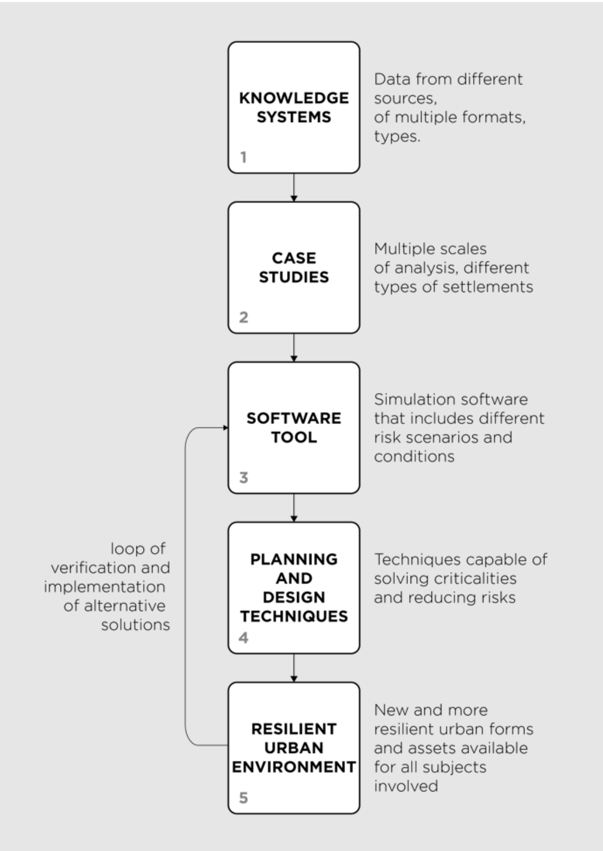

Fig. 1. Methodology diagram.

The final objective is to use the software application developed for the evacuation simulation (phase 3) to optimize the urban structure of the city, improving its performance and thus making it more resilient. In particular, we aim to employ a programming language in a digital setting that allows us to describe the behaviour of agents (modelling for example, human beings) at an urban size, as was previously mentioned in Section II. The GAMA Platform was selected as the key technology [15].

Processes in GAMA can be effectively conducted thanks to a programming syntax (based on Java) which enables variables of various sorts to be defined and associated with each other. The parameters of the simulations, or experiments, whose settings enable the display of findings in a variety of forms (among which animated maps, 3D models, graphs, etc.), are explained by the variables created, which serve as the algorithm's core. Additionally, multiple sorts of information, including geographic and geometrical (two- and three-dimensional) information, can be imported and shown. Table 1 depicts in the first column (Section *One*) the typical organization of a GAMA script. The table also reports in the second column some description of the Section by also referring to the code we developed for our experiments, and in the third column reports the code (or pseudocode) of the implemented script.

TABLE I. GAMA Pseudocode

Section	**Simulation**	
	Description	***Pseudocode***

Global	In this section shapefiles (.shp, containing geometric data about roads and buildings) are imported in the simulation environment. Street.shp are triangulated in order to generate a graph of streets (linear element). Buildings .shp contains data about the number of "potential" users of each facility. Agents representing that amount of users are created in the simulation environment using these data.	**global** {
		Import shapefile
		init {
		create object from: **shape_file_streets** ;
		object the_object <- **first**(**object**);
		triangulation of the object to get the different triangles of the polygons
		creation of a list of skeleton from the object
		//Split of the skeletons list according to their intersection points
		Creation of the graph using the edges resulting of the splitted skeleton

Species	In this section, a set of agents are defined. They model reflexes, interactions, aspects, behaviors and instructions for each species of agent. In our experiment we defined an agent for building, people, triangles, skeleton of the graph and the goal of the experiment we simulate. In the following column we report the GAMA code for the *people* agent People are represented as blue spheres (in the code: **aspect** sphere3D {
	
	draw sphere(1) **color**: *#blue*;)
	
	------ 	
	and interact with the environment scripted in the first section following the streets graph. Their main reflex is to first calculate the
		species people **skills**: [**moving**] {
		goal target;
		path my_path;
		reflex goto {
		do goto on:**the_graph target**:**target speed**:1.0;
		}
		aspect sphere3D {
		draw sphere(1) **color**: *#blue*;
		}

Section	Simulation	
	Description	*Pseudocode*
	shortest path between their original location (inside each building) and the arrival point (represented as a red dot). People agents follow the shortest path moving on the street graph at a fixed speed and disappear as they reach the red dot.	

Experim ent	The graphic user interface is defined in this section. Here it is possible to select the species that the simulation environment must represent in 3D according to the parameters defined in the section "species".
	
	This section aims to Visualize in three dimensions the urban environment and the people movements, interactions and behaviors.
		experiment prova_poligonalizzazione **type: gui** {
		output {
		display objects_display **type: opengl** {
		species object aspect: default ;
		species triangle_obj aspect: default ;
		species skeleton aspect: default ;
		species building aspect: default ;
		species people aspect: sphere3D ;
		species goal aspect: default ;
		}
		}

The initial section in the script, titled "global", deals with the general modelling parameters, to which the information in the following two sections refer. This part outlines the initial tasks that the simulation's engine performs once it is started, including the importing of libraries and fundamental files—such as files of a geographic type—as well as their handling and usage strategy. The second section of the script, named *species*, deals with the characteristics of the various species of agents that act as the simulation's main characters. In our preliminary study, we define four species that are individuals, buildings, arrival points, and street graphs. In Table 1 we report the code for the species *people* that defines the behaviors or reactions that the agents must have with respect to the various species (for instance, in this case, we define the kind of movement individuals must do by a roadway graph). Then, in the third section, we set the experiment's outputs that, in the experimental application described in Section IV, will then be graphically shown instantaneously as the modelling process is carried out.

IV. Some preliminary results

This section describes a preliminary and simplified application of the simulation carried out on a residential area in the first periphery of the city of L'Aquila, close to the Coppito University Campus of the University of L'Aquila (IT) that hosts the Department of Data Science and Informatics.

The first step was to construct the knowledge system, which through parallel scientific research we are preparing in the form of the Urban Digital Twin. The open-data geoportal of the Abruzzo Region is accessible at http://opendata.regione.abruzzo.it/ and contains the information necessary for the formulation of the analysis of the evacuation from campus buildings, during a disaster event, to an assembly point/waiting area. The most recent official information available, which is the Technical Regional Map from the local territorial database updated to 2007 (which contains shapefiles containing the road and building system's geometry), was specifically utilized.

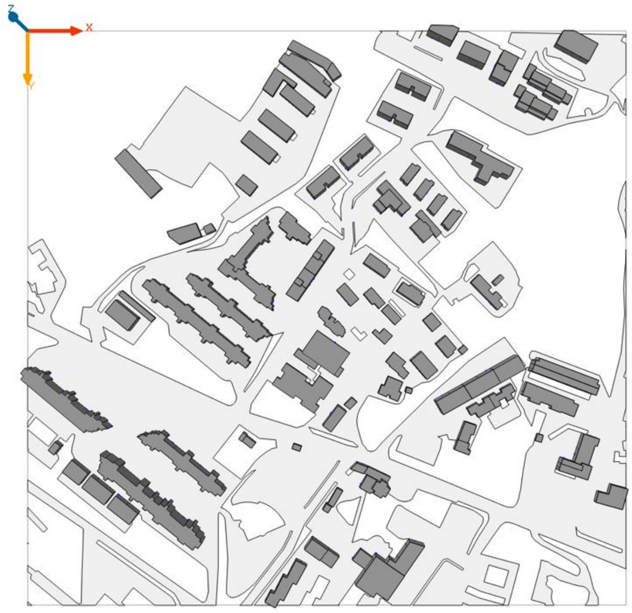

Fig. 2. Base 3D map implemented in the visualizer.

It is important to prepare the shapefiles in a GIS (Figure 2) before using them within GAMA. The number of hypothetical residents in each building must be determined to do crowd evacuation simulations. Since this type of information is not readily accessible on institutional portals or regional databases, this operation was conducted by considering 1 person per 100 cubic meters. We use this buildings' shapefiles that hold height values above ground for each geometry. The theoretical population can then be calculated using the intrinsic geometric properties of the structures and a straightforward division (performed sequentially and automatically for each building).

The procedures performed by the code are consecutive and operate by the simulation software's intrinsic functionality. The simulation's success depends greatly on the succession of the activities. The simulation software imports shapefiles. In terms of geographical representation only, the preliminary result (Figures 3 and 4), in which the urban environment may be shown in three dimensions, is not much different from what can be obtained using a typical GIS.

The most common practices in the area state that a road graph describing the flows that the agents that represent the inhabitants must travel to get to one or more specific sites (waiting areas) is required to perform a crowd simulation. This graph is constructed by the software application from the free areas (light grey spaces in Figure 3) in which people can move. The assembly point/waiting area that is taken into consideration denotes the position of a hotspot where residents can access and obtain first assistance given that the simulations are related to crises connected to natural catastrophes.

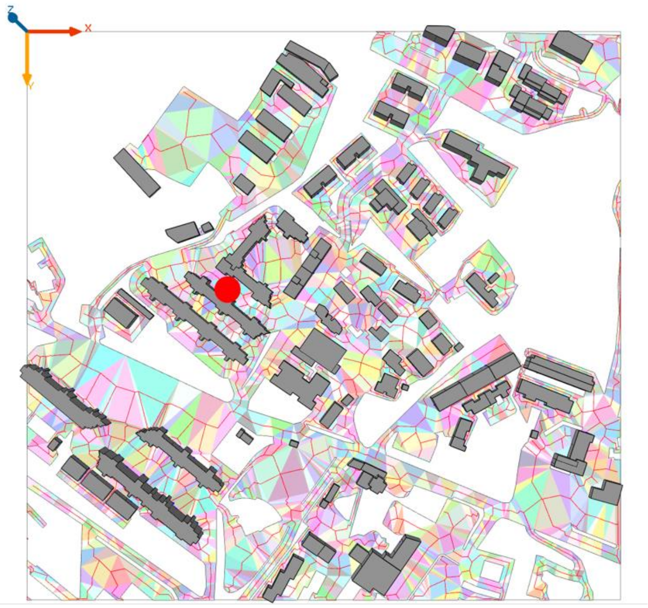

Fig. 3. Graph calculated from the polygonal road shapefile with agents flowing on it pointing to the hotspot (the red dot in the upper right side of the figure).

The road spaces depicted in Figure 2, are processed in a system of triangular geometries characterizing the road network (the colored triangles in Figures 3 and 4) and were automatically calculated in GAMA to produce the road graph.

The calculated graph is shown as a red line in Figures 3 and 4. As the study is currently in its testing stage to comprehend the features and characteristics of the programming syntax and the opportunities of using it to describe the behaviour of the crowd with increasing levels of detail, only one waiting area has been identified (red dot) placed on the graph itself for the time being.

Then, using the algorithm, agents representing the hypothetical residents of each building are created. The agents 'leave' the buildings at the beginning of the simulation and move in the direction of the red point via the shortest path. The agents, shown in Figures 3 and 4 as the little blue spheres, now move sequentially on the red graph and converge towards the red point that represents the hotspot.

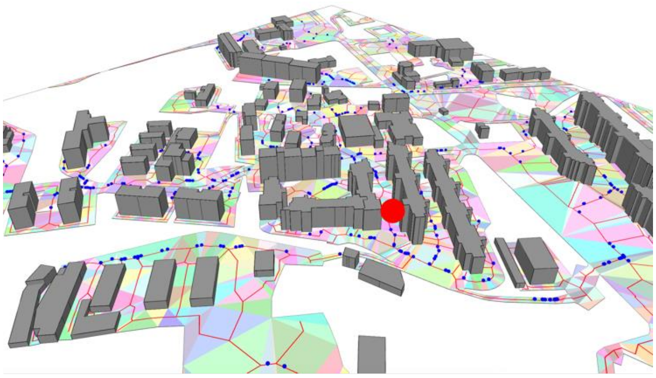

Fig. 4. 3D model of the running simulation where agents converge on the hotspot (the red dot in the middle of the picture).

It is important to note that the research currently comprises a few approximations (such as the crowd movement) for which more testing is being done.

The simulation of evacuation depends on several factors. It is modified according to the spaces that can be traversed by people and thus the open spaces. Therefore, by modifying the shape of open spaces, e.g., by removing obstacles, the performance of the urban structure can be improved, and people can reach the waiting area more quickly and easily. At this stage of the research, we are therefore modifying the system of open urban spaces and applying new simulation cycles (the feedback from stages 3-5 of the methodology) aimed at improving evacuation times, reducing risk and consequently increasing urban resilience. Therefore, the research's first results are helping us identify innovative urban design techniques useful for improving the shape of open spaces and increasing urban performance and safety during a disaster event. However, this phase is in its beginning stage, and we are expanding it to other scales of urban and territorial analysis, to integrate the techniques identified for the safe city.

V. Conclusions and Future Developments

The article describes preliminary results of a study concerning the simulation of the evacuation of people during a disastrous event. This simulation aims to define innovative urban design techniques aimed at reducing urban risks, increasing the safety of the city and therefore its resilience. The use of a evacuation simulation tool to improve the performance of the urban structure is also innovative.

For the simulation, a simplified application was prepared with Gama Platform, a modeling and simulation development system for the creation of spatially detailed agent-based simulations. The experimentation areas are cross-scale and have the objective of detecting urban criticalities at different scales and integrating different design techniques.

In the current state of the simulation, at least two simplifications have been made: the use of a simple movement graph, without alternative parallel paths, and the choice of a single waiting area. These two are limitations that will be removed in the continuation of the research, categorizing the structure of the open spaces and, in collaboration with the university's security offices, identifying a system of waiting areas. With the help of this interaction, it will be possible to accurately check the intended allocations and, as a result, the facilities' capacity considering the crowds that would really congregate there.

Future studies also will focus on refining the algorithm's (script's) treatment of crowd behaviour. As was already established, the agents now align themselves in accordance with the street graph as they orderly converge towards the collection location. This is a rough estimate. Especially in the case of unexpectedly catastrophic events, crowds adopt non-linear (or wandering) behaviour because of panic, disorientation, a lack of proper preparation for the worst-case scenario, and a natural desire to protect oneself and loved ones. In any case, the research's initial findings enable visualization of a hypothetical local population's initial response to a risk scenario. By creating risk (and multi-risk) scenarios with varying intensities, the goal is to expand the area of analysis to the entire built-up area after the methodology has been tested and validated on smaller and therefore more manageable case studies. This will help create a reliable planning support tool that can validate a-priori planning decisions. Furthermore, because the data utilized are accessible across most of the Italian territory, this method and its procedures are repeatable and usable in different situations.

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