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Antonio Bucchiarone*, Annapaola Marconi*, Gernot Bahle†, Paul Lukowicz†, Andreas Poxrucker†, Alessandra Russo‡
*Fondazione Bruno Kessler, Trento, Italy - {bucchiarone,marconi}@fbk.eu
†DFKI GmbH, Kaiserslautern, Germany {gernot.bahle,paul.lukowicz,andreas.poxrucker}@dfki.de
‡ Imperial College, London, UK - {a.russo}@imperial.ac.uk

***Abstract*—Modern software systems are becoming more and more socio-technical systems, composed of distributed and heterogeneous entities from a mixture of people, their environment and software components. These systems operate under continous perturbations due to the unpredicted behaviours of people and the occurrence of exhogenous changes in the environments. For a socio-technical system to be resilient, adaptation must be collective, that is multiple entities must adapt simultaneously in a way that addresses critical runtime conditions whilst preserving the benefits of the collaborative interdependencies. In this paper, we present a framework for the development of large-scale, collective and adaptable systems where adaptations are resolved in a decentralized but collaborative fashion. Our proposed collaborative adaptation is driven by the system awareness of the ramifications that arise from the interdependencies between entities, and aims at minimising the impact that changes will have on such interdependencies. Decisions about what and how to adapt are therefore determined through a process of collaborative resolutions of interdependent critical run-time conditions that see the involvement of affected entities. The framework is instantiated in the context of a smart mobility scenario through which its main features are illustrated and evaluated.**

Keywords—Collective Adaptive Systems, Self-adaptation, Dynamic Adaptation, Multi-criteria Decision Making.

I. Introduction

The term *ensemble* has recently been introduced in the literature to denote very large-scale systems of systems that may present substantial socio-technical embedding [?], [?]. They typify systems with complex design, engineering and management, whose level of complexity comes specifically from bringing together and combining in the same operating environment many heterogeneous and autonomous components, systems and users, with their specific concerns. To be robust against the high degree of unpredictability and dynamism of their operating environments, and to sustain the continuous variations induced by their socio-technical nature, ensembles need to *self-adapt*.

Self-adaptation is an important feature of many complex software systems, but it is often seen as a means to automate management activities in order to meet desired requirements, such as minimise resources and costs (e.g.[?]). In an ensemble-based approach, self-adaptation is instead a feature of the collectiveness. Individual entities may "opportunistically" enter in an ensemble and self-adapt in order to leverage other entities' resources, functionalities and capabilities to perform their task more efficiently or effectively. But, the collaborative nature of the ensemble, makes this self-adaptation much trickier. Changes in the behaviour of one entity, as a result of its own self-adaptation, may break the consistency of the whole collaboration, or have negative repercussions on other participants in the ensemble. Adaptation must therefore be *collective*. Entities within an ensemble must be able to self-adapt simultaneously but, at the same time, preserve the collaboration and benefits of the ensemble they are within. Self-adaptation of an individual entity is therefore not only finalised to the achievement its own respective goals but also to the fulfilment of emerging goals of the dynamically formed ensembles.

This paper addresses the challenge of collective adaptation by proposing a notion of *ensembles* that enables systems with collective adaptability to be built as emergent aggregations of autonomous and self-adaptive entities. In our approach, ensembles have several key properties. They can be created *spontaneously* and change over time: different entities may decide to join and/or leave an existing ensemble dynamically and autonomously. Termination of ensembles may also be spontaneous. It may occur when some or all entities, involved in an ensemble, leave because, for instance, they have reached their goals, through collaboration, and the collaboration has ceased to provide them additional benefits. Building upon this notion of ensemble, we present a distributed adaptation approach for systems composed by ensembles: collections of entities' roles with their respective goals and preferences. Adaptation in these systems is triggered by the run-time occurrence of an extraordinary circumstance, called *issue*, and it is handled by an *issue resolution* process that involve entities, affected by the issue, to collaboratively adapt with minimal impact on their own preferences. Alternative adaptations may be available, and given the multiple criteria and preferences of the different entities involved in an ensemble, such adaptations may need to be ranked. Central to our approach is therefore the use of a multi-criteria ranking approach, based on *analytic hierarchy process* (AHP), that allows to select adaptation alternatives that are best with respect to the preferences of the entities involved. The approach is instantiated in the context of a smart mobility scenario and in particular using an urban mobility system composed of several means of transportation, passengers and management related entities. Key properties of our approach are the emphasis on collaboration towards fulfilment of individual diverse goals and the heterogenous nature of an ensemble with respect to roles, behaviours and goals of its participants. These properties distinguish our approach from other types of ensemble models, like for instance swarms, where all elements of a community have a uniform behavior and global shared goal [?], [?], and multi-agent systems and agent-based organizations [?], where there may be several distinct roles and behaviors, but the differentiation is still limited and often pre-designed. We have instantiated our approach is instantiated in the context of a smart mobility scenario and in particular using an urban mobility system composed of several means of transportation, passengers and management related entities.

The paper is organised as follows. Section II motivates the need for distributed and collective adaptation and discusses challenges and requirements. Section III presents our solution which is based on the *Ensemble* concept. In Section IV we present the formal framework and the algorithm for collective adaptation that is applied and evaluated in Section V using a scenario in the smart mobility domain. We conclude the paper positioning it with respect to the related works in Section VI and discussing some points to future work in Section VII.

II. Motivating Scenario and Research Challenges

Modern cities attempt to flexibly integrate transportation options for residents and visitors to use buses, trains, taxis, bicycles and cars. They play an important role in the economy of the city and the quality of life of its residents. In this chapter we consider a simplified urban mobility system (UMS), that comprises several means of transportation that are collectively managed. We focus on the aspect of adaptivity and are interested in situations where computational entities and affected human (e.g passengers, drivers) collectively reach adaptation decisions. In the following we describe the scenario and demonstrate the challenges it poses to collectively adapting socio-technical systems like UMSs.

A. Urban Mobility System

The UMS consists of the following means of transportation: *Regular bus service*, a network of fixed bus routes with fixed timetable; *Flexible Bus (FB)*, a service that collects trip requests from customers and organises on-demand routes that efficiently serve the requests; *Car Pool*, a service to share car journeys so that more than one person travels in a car, and *Taxi*, a conventional taxi service. Each means of transportation has a complex internal substructure. For example the FB service allows third party minibus owners to register their availability for serving trips, and customers to register trip requests (e.g., location, time). The service dynamically creates routes on the basis of time and location of the trips requested and the availability of vehicles. Each FB route is essentially an ensemble composed of the vehicle (or FB driver) that is supposed to serve the route and passengers travelling within the same (or close) time and location span. A FB route is supervised by the FB company that provides all necessary infrastructure. It is easy to see that a FB route is a good example of collaborative behaviour: passengers "sacrifice" part of their flexibility in order to travel cheaper, compared to a taxi, and quicker compared to conventional buses.

Our Urban Mobility System (UMS), integrates three means of transport: regular bus (RegBus), Flexible bus (FlexiBus) and car pooling (CarPool) and a set of entities that can communicates in different ways. Entities can be part of several possible ensembles (i.e., from E1 to E9) according to their needs. Figure 1 shows the topology of the UMS example. It includes a hierarchical pattern but also direct relations (as in the Ensemble E9 composed by the FlexiBus Company (FBC) and the Car Pool Company (CPC).

The following situations illustrate when a running FB route could trigger adaptation: one of its passenger is late for the bus; one of its passenger decides to no longer travel; the bus is damaged in an accident; the FB company decides to change the route in order to adapt to traffic conditions.

Even though, the cases above seem to be quite natural for any on-demand transportation service, tackling them is not always trivial. For example let us to consider the case when a bus is damaged or it is in a strong delay. In this case all passengers must be proposed alternatives and/or compensations.

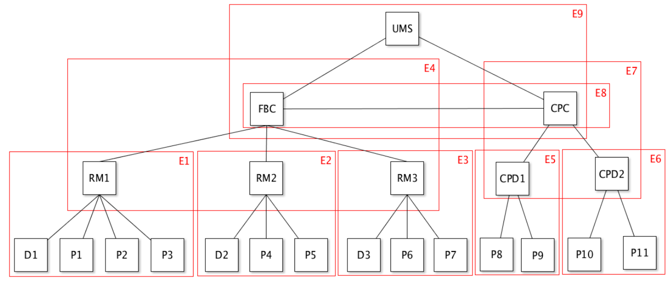

Fig. 1: Types of entities and Ensembles in the UMS.

The solutions could be any or a combination of the following cases: 1) reassign passengers to other routes; or 2) reassign (groups of) passengers to other means of transportation (e.g., recombine the passengers into small groups and assign them to taxis or car pools). In the following subsection we analyse the challenges posed by the UMS scenario.

B. Challenges

The principal actors in the UMS scenario (i.e., passengers, FB drivers, FB company, etc.) are quite autonomous and generally act independently. This makes the system highly dynamic and distributed. The surrounding environment of an actor changes frequently and unpredictably (e.g. as other actors may unpredictably change their mind) and therefore the system requires constant monitoring and adaptation.

Existing approaches (see Section **??**) normally deal with multi-agent adaptive systems through isolated adaptation: each actor adapts itself independently from each other. However, in our scenario the problem is complicated by collective behaviour. Even though entities are generally autonomous, they dynamically form collaborative groups, called *ensembles*, to gain benefits that otherwise would not be possible. The example of such an ensemble is a FB route (E1 in Figure 1) which coordinates the adaptation behavior of multiple entities (FB driver, passengers, and FB company) and in return gives them certain benefits (e.g., cheap and fast way of travelling).

Membership of an ensemble may temporarily reduce the flexibility of its entities. Within this context, isolated entity self-adaptation is not effective. We can easily imagine what happens if a passenger books a trip with a FB and then silently changes its mind and decides not to travel. It is likely to cause unnecessary delay for the route (e.g. the bus will have a redundant stop) and raise the cost of the trip for the remaining passengers, including probably extra charges for the cancelling passenger. Even more serious consequences arise if a bus gets damaged: isolated adaptation by the bus driver could totally break the passengers' travel plans. Adaptation has to take into account not only customers trip requests but also customers constraints and preferences. For example, a particular passenger may want to avoid travelling through unsafe areas in the city, but a possible re-planned route may pass through such area.

In adaptive systems with collective behaviour new approaches for adaptation are therefore needed that allow (i) *multiple* entities to collectively adapt with (ii) *negotiations* to decide which collective changes are best.

Collective adaptation also raises a second important challenge: which parts of the system should be engaged in an adaptation. This is not trivial at all, since solutions for the same problem may be generated at different levels. For instance, a passenger's delay may be resolved in the scope of a FB route, by re-planning the route, or in the wider scope of the FB company, with the engagement of other routes, or even in the scope of the whole UMS, with the engagement of other means of transportation such as a car pool. The challenge here is to understand these levels, formalize them and create a mechanism that decides the right scope for an adaptation for a given problem.

The hierarchical nature of an UMS opens up all these alternative options. Within our scenario, we can identify several hierarchical levels of abstraction that operate at different scales in time and space. An FB route combines passengers with a driver, a Flexibus company combines FB routes, and an UMS combines a Flexibus company and other means of transportation. The higher the level of abstraction, the wider the scope of adaptation.

In the next sections we introduce our approach that addresses the challenges above in order to facilitate collective adaptation.

III. Overview of the Approach

IV. Formal Model

V. Evaluation

VI. Related Work

VII. Discussion and Future Work