INTERNATIONAL DESIGN CONFERENCE - DESIGN 2016
Dubrovnik - Croatia, May 16 - 19, 2016.

# AGENT-BASED SIMULATION FRAMEWORK TO SUPPORT MANAGEMENT OF TEAMS PERFORMING DEVELOPMENT ACTIVITIES

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*Keywords: agent-based approach, design teams, design process simulation*

## 1. Introduction

The efficacy of developing and introducing new products is the result of organization's development activities [Salerno et al. 2015], coupled with its intangible resources (human, structural, relational) [Griffin et al. 2014]. Rather than being specifically related to exceptional individuals, successfully developed innovations are contributed by the entire organization, largely as a result of developers' joint activities. As such, both individual and teamwork development activities are key operation elements of every development organization. Effective teamwork can result in development time reduction and quality improvement. It involves good communication and coordination, balanced contribution of individuals, mutual support, effort, and cohesion [Hoegl and Gemuenden 2001]. Being successful in these aspects of teamwork is not only beneficial for the project, but also for individuals who gain knowledge and personal satisfaction.

While team activities play a significant role in product development, only a small proportion of research on cooperation and interaction between team members exists in comparison to studies that examine activities with an individualistic focus. Teamwork does not result simply from aggregating the behaviour of individuals, nor can its outcome be measured at the scale of individual units. The knowledge and information flow in development organizations, and information processing by different actors of the development processes affect many aspects of organizational dynamics such as beliefs, norms, trust, decision making, learning, and innovation. Organizations with their teams and individuals inside teams can thus be seen as complex socio-technical systems [Oyama et al. 2015]. This complexity grows as some organizations create multi-team environments, where individuals have multiple team memberships, and team boundaries are often ill-defined [Crowder et al. 2012].

### 1.1 Team structure and activity distribution

Project managers involved in engineering systems development need support in the form of methods and tools that will help them deal with challenges arising from team formation and teamwork complexity. Complex projects led by small and medium-sized enterprises (SMEs) or networks of SMEs require selection of optimal team composition, planning of the work activities, and early identification of project risks related to the individual and team performance. The selection of individuals to compose a work team is not a trivial task because it must not only consider competencies and availability, but also personal and social characteristics of each potential team member [Martinez-Miranda et al. 2006]. Manager's perspective can be improved with a better insight into team's interaction and knowledge networks (who communicates with who, who knows what, what knowledge and resources do particular activities require), team's shared mental model, and individual's characteristics such as social skills, learning ability, availability, response rate, motivation, etc. [Crowder et al. 2012]. Development of methods and tools for gathering such data requires monitoring and measurement of individuals and teams performance by longitudinal studies of product development projects (e.g. activities work sampling [Robinson 2010], [Skec et al. 2015] and empirical studies of specific activities such as problem-solving or ideation [Cash et al. 2014, 2015], [Cash and Storga 2015]). Longitudinal research studies tend to be time and resource consuming, with results that are often applicable only to the particular context of the observed organization. Moreover, aforementioned observational and work sampling studies are limited by the size of the sample. To validate the study findings entirely, it would be necessary to monitor a larger number of participants across different contexts. Combining results of such research with the advances in information technologies opens a space for utilizing simulations of teamwork in development processes as a potential research and management tools. Interest to use the simulation as a research tool to study product development processes is in evading the time costs and resources of longitudinal studies. Furthermore it can sometimes take years before the long-term effects can be analysed, for example the success of innovation on the market.

Aim of the paper is to explore simulation as a management tool to help managers in the planning of team composition and activities within the development process and investigate if project planning could be enhanced by relative performance comparison of teams composed of different individuals working within different types of development projects. Both points of interest provide the need for a simulator of development processes in which individuals are simulated to work and interact in teams and perform individual and teamwork activities.

## 2. Related work

Agent-based modelling has proven to be an efficient tool for modelling organisations and simulating human behaviour. The bottom-up approach enables researchers to examine outcomes emerging from human and organisational characteristics and rules implemented in a model. Thus, various general purpose teamwork models have been developed.

Fan and Yen [2004] provide an extensive overview of general purpose teamwork models in which agents are used as a support. Systems like GRATE* [Jennings 1995], STEAM [Tambe 1997], and CAST [Yen et al. 2001] are analysed with the focus on communicative, helping and collaborative behaviours, as well as the scope of shared mental model implemented in each of them. In these systems, agents interact with each other or with humans and can serve as substitution of humans in a team. The main purpose of these systems is simulating and supporting teamwork behaviours to improve team effectiveness.

There is, however, a different approach to modelling teams. In models like VDT [Jin and Levitt 1996], TCM [Rojas-Villafane 2010] and NetWatch [Tsvetovat and Carley 2004], etc. agents are the representation of human individuals and possess some human characteristics like motivation, personal trails, memory or learning ability. These models are suitable for team profiling and examination of the effect of special features on team performance. Indeed, as stated in [Rojas-Villafane 2010], these models are used to predict team performance taking into account job, human and organisational factors.

### 2.1 Agent-based modelling of collaborative product development

Distinction in the purpose and usage of agents also exists when modelling collaborative product development. Thus, some agent-based models are used for providing support in solving design problems or as environments that enable cooperation among designers. Such models are for example SHARE [Toye et al. 1993], PACT [Cutkosky et al. 1993], Hao et al. [2006] model, Wang et al. [2009] model. Madhusudan [2005] developed a framework for distributed design process management were specialised design roles are given to autonomous agents and cooperation between them is managed by the central agent.

A-design [Campbell et al. 1999] is methodology where agents represent individual specialists in a team while working on the same activity. They possess different knowledge and strategies enabling them to provide a variety of design solutions. Solutions are iteratively evaluated and improved until a satisfying solution is obtained. Similar approach was taken in [Olson et al. 2009], where an agent-based simulator was used to simulate behaviour observed in design group at NASA's Jet Propulsion Laboratory called

Team X, and in CISAT (Cognitively-Inspired Simulated Annealing Teams) [McComb et al. 2015], recently developed modelling framework that incorporates eight theory- based characteristics of teamwork in design. Although in mentioned models agents are used to simulate humans and, for example, are capable of reasoning and learning, the primary purpose of these models is to search through solution space and provide designs comparable to, or better than, solutions obtained by designer teams. However, none of the mentioned product development teamwork models focuses on social interactions, communication patterns, trust or other social characteristics influencing the performance of product development team, nor provide insights in exact project execution process. Thus, those models cannot be used for team profiling.

For managerial purposes such as finding an optimal work distribution, potential problems in activity performance or profiling of product development team, previously mentioned VDT and NetWatch can be used, as well as [Zhang et al. 2009, 2012], TEAKS [Martinez-Miranda and Pavon 2012], [Crowder et al. 2012], [Dehkordi et al. 2012], and [Singh et al. 2013]. An overview of key positive and negative characteristics of these models is given in Table 1.

**Table 1. An overview of key characteristics of agent-based models applicable for profiling of product development teams**

| Model/ reference | Key characteristics | Limitations |
|---|---|---|
| VDT [Jin and Levitt 1996] | - covers complex and real projects<br>- detail modelling of agent's characteristics and behaviour<br>- inclusion of error possibility, noise in communication and exceptions<br>- inclusion of various communication tools and their properties<br>- inclusion of formal team activities<br>- earlier versions (used for product development simulation) extensively validated | - prescribed activities<br>- agents do not differ in terms of competences, social characteristics, motivation or goal commitment<br>- agents not capable of learning<br>- no team trust or social interconnections modeled |
| NetWatch [Tsvetovat and Carley 2004] | - proactive, intelligent agents capable of determining other agent's needs<br>- modelling of transactive memory and agent learning<br>- inclusion of homophily and social proximity<br>- detail knowledge diffusion modelling | - preschedule activities<br>- difficult to represent knowledge needed for project completion as bits |
| [Zhang et al. 2009], [Zhang et al. 2012] | - activity scheduling based on utility function<br>- inclusion of unplanned meetings and interruptions | - collaboration just between two agents<br>- social competences of agents not modelled |
| TEAKS [Maritnez- Miranda and Pavon 2012] | - social and emotional aspects modeled in detail<br>- inclusion of collaboration between three or more agents | - predefined and prescribed activities<br>- focused only on emotional state of an individual, neglecting technical aspects |
| [Crowder et al. 2012] | - simple, clearly defined rules<br>- inclusion of social and technical aspects | - workflow predefined, activities prescheduled and preassigned to agents<br>- no empirical validation provided |
| [Dehkordi et al. 2012] | - detail innovation and creativity measurement<br>- modelling impact of work overload on innovation<br>- inclusion of characteristics such as stress level, desirable level of challenge, and modelling motivation change | - other aspects of design process not modelled |
| [Singh et al. 2013] | - detail modelling of agent's perception (transactive memory)<br>- inclusion of learning by observation | - other aspects of design process not modelled<br>- not applied to concrete design problem |

## 3. Simulation framework

Literature review revealed many possible perspectives and approaches to model product development teams. However, some of them concentrate on detail modelling of single aspect and simplify or completely ignore other aspects. Finding an appropriate level of abstraction, i.e. capturing enough detail to properly represent collaboration, communication and activity performance, while avoiding to obtain uninterpretable results, is a difficult task. In order to obtain the desired level of detail of interactions and granularity of development processes (phases, activities and tasks), a simulation framework is proposed. The framework (Figure 1.) consolidates three main segments: configuration of simulation inputs, the simulation model, and the outputs during and after the simulation runtime.

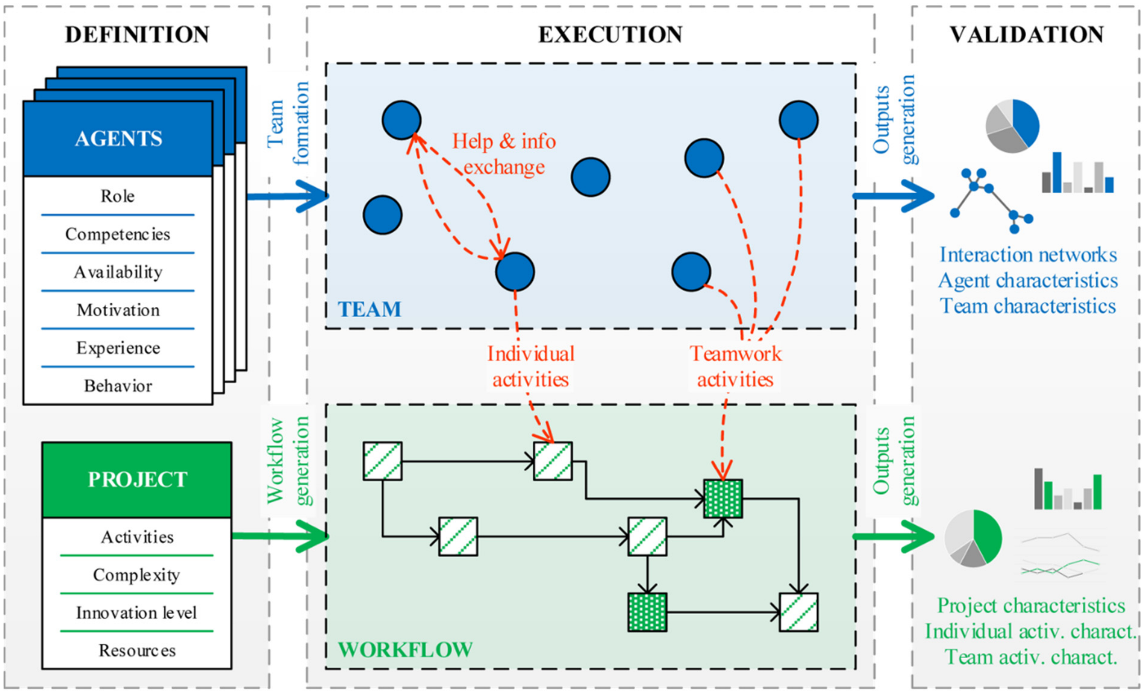


**Figure 1. Simulation framework**

### 3.1 Simulation definition

Simulation inputs are divided into two segments. The first one is the configuration of individuals, that is, agents that will take part in the simulation. The second aspect of simulation inputs is the configuration of the development project (in terms of workflow) to be simulated. Project characteristics are reflected in the workflow of activities that is generated at the beginning of the simulation.

Agent characteristics (its variables and parameters) are the main drivers of agent's behaviour during the simulation. Both individual and teamwork activities' executions within the simulation are influenced by characteristics of agents that take part in the activities. Different settings can result in different duration of activities, different tendency to iteration and a different number of information flows within the team. The following categories of agent's characteristics are included in the simulation framework:

- Role - portrayal of tasks an agent has to perform during the project. The role determines the type of activities agent can be assigned with (domain-specific activities), but can also affect leadership. Examples of roles are design agent, team leader agent, etc.
- Competencies - individual-level characteristics that are related to both the ability of agent executing specific activities (knowledge and skills) and to the social aspect of agent's personality. Knowledge and skill competencies represent the extent to which agents are able to perform both technical and non-technical activities [Robinson 2010]. Social competencies

represent extraversion and communication skills - rather an extent to which team members are sociable, talkative, assertive, active or retiring, sober, reserved, cautious [Reilly et al. 2002].

- Availability - a characteristic that reflects both spatial and temporal availability of an agent during the simulation. Temporal availability is the amount of working time agent can spend on project activities. Spatial availability defines the amount of working time the agent is collocated with other team members thus enabling implementation of distributed development.
- Motivation - the extent to which agents are committed to achieving the project goals. Competencies alone are not sufficient for designers to perform activities - they also have to be motivated to do so [Crowder et al. 2012].
- Experience - a characteristic that covers both experience in certain activities and working with certain agents. In both of these aspects experience is highly related to project efficiency [Littlepage et al. 1997], [Sivasubramaniam et al. 2012]. Furthermore, experience in executing certain activity together with certain agents can also be recorded.
- Behaviour: a strategy agents take when faced with problem-solving. This problem-solving style is the thinking and behaviour agent engages in to obtain the desired outcome [Treffinger et al. 2008]. Multiple dimensions of problem solving can be incorporated including creativity [Treffinger et al. 2008], the radicalness of thinking, information processing, decision-making [Cayzer 2015] and other.

Project customization should allow modelling of workflows and environments that reflect different types of product development projects and organizations. Project characteristics should drive the generation of workflow and affect its structure - mainly activity dependence and iteration. The following project characteristics should be included within the simulation framework:

- Activity type: characteristics of project activities that will constitute the workflow. A library of development activities (e.g. [Song and Montoya-Weiss 1998], [Fairlie-Clarke and Muller 2003], [Sim and Duffy 2003]) should enable tailoring of project activities according to organization's product development process. Activity fragmentation should further allow to simulate only specific activities or phases within the project.
- Complexity level: nature, quantity, and magnitude of organizational activities and activity interaction posed by the project [Tatikonda and Rosenthal 2000]. Complexity can also be a result of the product being developed, e.g. the number of functions this product has to perform [Griffin 1997]. Higher complexity brings more interdependencies and iteration in the process.
- Innovation level: the (technology) novelty of product being developed, describing the degree of familiarity with the given technology [Tatikonda and Rosenthal 2000]. Projects are often perceived as incremental (adaptive) or radical innovation [Song and Montoya-Weiss 1998], [Cardinal 2001], [Holahan et al. 2014], depending on the amount of the product that has to be redesigned [Griffin 1997]. Innovation level affects uncertainty, iteration, and requirements (on competencies, skills, experience and behaviour) of particular activities within the process.
- Resources: description of the environment in which the project takes place. It comprises all organizational and external resources that are available for the team. Resource configuration affects the activity efficiency due to information seeking and development support.

### 3.2. Simulation execution

For simulation to be executed a team has to be formed and a workflow has to be generated. The team gets composed of agents that will take part in the simulated project. Once agents are configured and the simulation starts, the computation of initial team characteristics is executed. Team characteristics emerge from the characteristics of individual agents. In some cases the calculation of team characteristics is simple, e.g. comparing competencies and reciprocal experience of agents to calculate team diversity, team ability and team tenure [Sivasubramaniam et al. 2012]. However, the calculation of team characteristics gets complex when it comes to team creativity [Leenders et al. 2003], [Bissola et al. 2014], team cohesiveness [Sivasubramaniam et al. 2012] and trust, and team cognitive style [De Visser et al. 2014]. Workflow is generated based on the project setup and represents a network of project activities. Workflows can differentiate in number and type of activities and structure (dependencies, concurrency, adaptivity and iteration [Browning and Ramasesh 2007], [Karniel and Reich 2011]).

Initially, a set of workflows could be developed based on the description of the different process types available in the literature. Additionally, workflows could be generated according to a set of predefined structuring rules and project setup characteristics. The team and the workflow are the inputs for the agent-based simulation. Activity manager (either the simulation executor or an agent) assigns individual activities to single agents and teamwork activities to multiple agents. Activities are assigned to agents according to their roles and competencies. When executing activities, if necessary, the agents communicate with other agents and resources to learn or receive help. Thus, two main types of activities are classified: individual and teamwork activities.

Activity execution depends on agent's characteristics, but also on the context in which agent performs. For example, the agent can execute the activity more efficiently with higher competencies and motivation, previous experience in similar activities and with an appropriate problem-solving strategy. Furthermore, the agent may need help or information from other agents or resources. The agent will, based on social competencies and previous experience in working with other agents, approach another agent and request attention. Availability, trust, motivation, experience and social competencies of other agents will determine if and how efficient they can transfer information or knowledge.

Formal teamwork among agents is undertaken within teamwork activities. Activity manager assigns two or more agents with a teamwork activity such as idea generation, decision-making, planning, resolving conflicts, etc. Unlike individual, teamwork activity execution is mainly influenced by team characteristics, that is, by the joint characteristics of agents involved in the activity. For example, teamwork activity execution is influenced by following team characteristics: team ability (competences), team tenure (experience in working with each other), team creativity, team cohesiveness, team trust and team cognitive style (problem-solving style). Behaviour of multiple agents during specific teamwork activities has to be enhanced with studies of teamwork, especially with empirical studies of ideation, decision-making, and planning.

During engineering design process there are interactions between individuals that are not considered formal teamwork [Skec et al. 2015]. In the framework, these interactions are modelled as an informal exchange of information like helping and learning. It can happen that an agent starts to work on an activity but lacks the time or some of the competencies to finish it. Agents then may apply strategy where they, for example, ask respectively other (more competent) agents for help. The first one to respond will help the agent to finish the work faster or gain the competence. Here again, the decision if to help or not depends on multiple factors, and so does the performance of the learning process.

### 3.3 Simulation validation

It is expected that agent and team characteristics change during the simulation. The change in characteristics of agents and teams and their interaction is represented in a form of simulation output data. Moreover, agents work on project activities individually or in teams, thus affecting project and activity characteristics. This change in project and activity characteristics is likewise the simulation output data. The following output categories have been included within the simulation framework:

- Interaction networks: insights into who communicated with who, who was helping who, who was providing and who was receiving information, and who was using what resources.
- Agent characteristics: change of initially configured agent characteristics (competencies, motivation, experience) and characteristics derived from interactions and activity execution (trust in other agents, response rate, help provided, help received, time spent in different types of activities and idle, activities completed, the number of iterations, etc.).
- Team characteristics: change of initially calculated team characteristics (team ability, team tenure, team creativity, team cohesiveness, team trust) and team characteristics derived from individual and teamwork activity execution (team motivation, team response rate, time spent in different types of activities and idle, team activities completed, etc.).
- Project characteristics: project performance (time, number of activities completed, which activities are performed at what time, which are the ongoing activities), proportion of activities and interactions during the project (amount of individual work, formal teamwork, requesting help, helping, receiving help, learning, idle), iterations and changes in workflow, and other.

- Individual activities characteristics: performance in individual activities execution, a proportion of different types of individual activities, interactions during individual activities, iterations, etc.
- Team activities characteristics: performance in formal and informal teamwork activity execution, a proportion of different types of teamwork activities, interactions during teamwork activities, iterations, etc.

Simulation outputs can be used to compare teams composed of different individuals (e.g. contrasting competencies, experience or behaviour) working on different types of development projects (e.g. adaptive or radically innovative).

## 4. Initial implementation of proposed framework for simulating two weeks of a project using the initial agent-based model of teamwork

### 4.1 Base model and model upgrades

Every model described in Section 2 poses some desirable features and covers some aspects of the framework proposed in Section 3. However, the model developed by Crowder et al. [2012] was found most suitable for a basis of the initial model version of proposed framework. This model includes desired agent's characteristics such as motivation, availability and competence level, as well as communication between designer agents and team trust. The team consists of designer agents representing team members and activity manager that delegates activities to designer agents. An activity is performed by one agent. During the simulation, designer agent attempts to perform an activity and, if its competence level is sufficient, successfully finishes it. In case it lacks the competence, other designer agents are requested for help. If an agent is not working on another activity, it provides information and receiving agent's competence temporarily raises. If none of the design agents provides help, the agent contacts a resource agent which is an equivalence of team member reading a manual and learning on its own.

While keeping the main idea behind the helping-learning algorithm, the initial implementation of proposed simulation framework includes some extensions. For example, competence is divided into skill, knowledge and social competence. When an agent attempts to perform a given activity, it checks whether both, its skill and knowledge, are sufficient. If it lacks any, it seeks help. However, instead of contacting all other agents, it gives priority to agents that have sufficiently high skills or knowledge (depending on what is needed), but also have high social competence, and provide fast and detail feedback [Martinez-Miranda and Pavon 2012]. On the other hand, the available agent that receives help request does not necessarily provide help but decides whether or not to respond. This decision is governed by agent's response rate value that decreases as agent spends time helping, and rises to the initial value as time passes without anyone asking the agent for help. As modelled in Crowder et al. [2012], the time needed to raise competencies to sufficient level depends on the difference between helper's competencies and competencies of the agent asking for help, but also on learning rate of the agent receiving help. If the agent is learning on its own (i.e. reading a manual), it takes more time to raise its competencies.

Another important modification was made by adding formal and informal team activities. Formal team activities are team meetings with predefined start time, duration and attendees. A variable was included defining a maximal number of minutes an agent spend idling between activity end and the start of a formal team meeting. In other words, if an agent finishes an activity when a short period is left till formal meeting start, the agent is not going to start performing a new activity. However, if team meeting starts and the agent is still performing another activity, it is going to arrive late at the meeting. Informal team activities are discussions with prescribed number of participants and duration, but exact participants are not prescribed. When a (randomly chosen) agent needs to have a discussion, it sends an invitation to others, and they reason whether or not to respond depending on their availability and response rate. When a required number of participants responds, discussion session is held, and afterwards participants return to their prescribed workflow.

Therefore, novelty in the modelling of agents and their behaviour include the inclusion of social competencies, skills and knowledge, a will to decide whom to interact with, and an ability to refuse to help if they have already spent too much time helping others. Furthermore, agents have diverse learning abilities, availability rate and willingness to respond to other agent's requests. Novelty in activity decomposition includes the possibility of more agents working on the same activity and holding discussions, and the inclusion of formal team meetings.

### 4.2 Simulating two weeks of a project

To obtain data for validation of the implemented model a team of 15 people working in the company focusing on systems for generation, distribution and transformation of electrical energy was selected and sampled over the course of two weeks [Skec et al. 2015]. The team was working on multiple projects at different stages and, thus, time and workload were not equally distributed between projects. Participants were sampled through the mobile application for work sampling and questionnaires. The mobile application provided simple, yet efficient way of dynamically gathering data on participant's daily activities. Each participant's mobile application emitted on average eight alarms a day, randomly distributed through working hours, and displayed input screens where participants recorded details about their current activities. Participants recorded which project they were working on, work type (individual technical, individual administrative, teamwork or break) and work subtype (discussion, meeting, etc.), activity type (planning, analysing, innovation/improvement, decision-making, etc.), who they were working with, what was activity execution manner, what was information transaction type and, finally, rated information importance for current project phase and their own motivation level. Data collected through questionnaires was used to calculate agent's initial motivation, availability and trust they have had in the team, and to predefine their workflow while leaving them a choice to participate in discussions, ability to choose a helper when needed, and decide whether to help others or not.

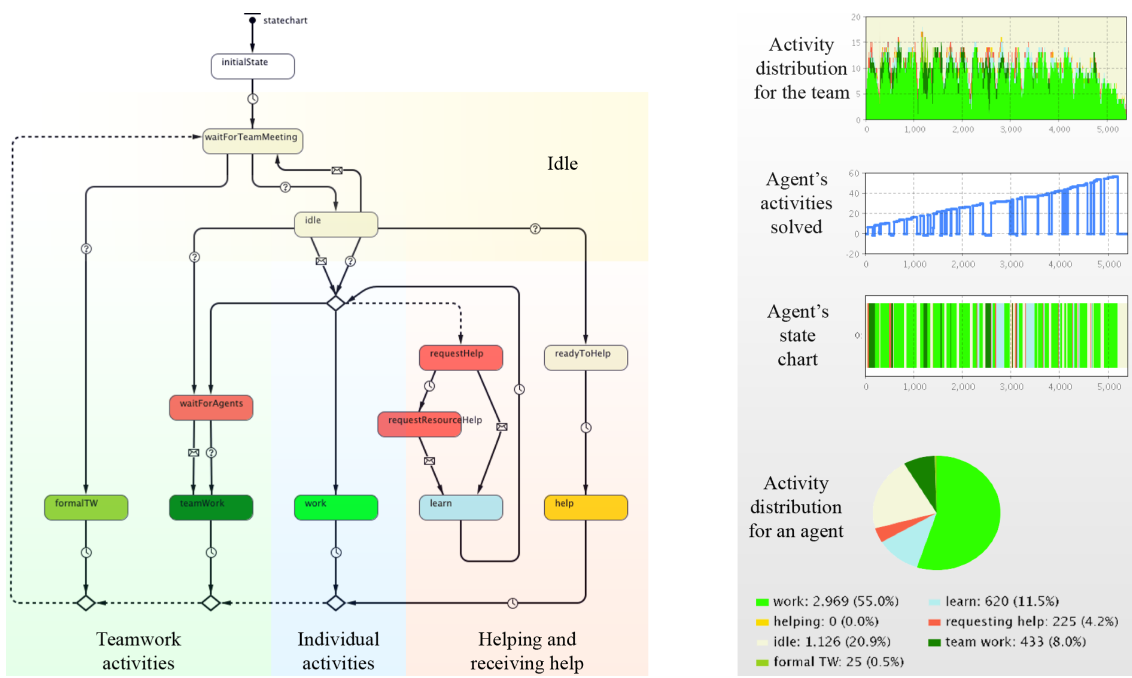


**Figure 2. Basic agent-based model flowchart on left and examples of simulation outputs on right**

Characteristics like learning ability, skills, knowledge, willingness to share knowledge (i.e. response rate) and to provide fast and detail feedback do not change significantly on weekly basis. Thus, data on those characteristics were collected through questionnaires where participants had to provide a rating of each other's characteristics, as well as evaluate themselves [Skec et al. 2015].

The model was implemented in AnyLogic simulation environment [AnyLogic 2015]. Basic designer agent's state chart was modelled as shown in Figure 2. Work periods (i.e. periods when the agent can start performing an activity or can be contacted for help) for every agent are randomly set at the simulation start, and each agent's state can be observed at every minute of simulation, as well as agent's interactions, a current level of skill and knowledge, it's response rate, motivation and trust. Furthermore, statistics such as a number of received, answered or sent requests for help, a number of discussions, etc.

are collected for every agent. Thus, at the simulation end, full agent's work profile can be obtained. Change in motivation, trust, competencies and response rate are presented by charts as shown in Figure 2. Pie chart representing the proportion of time spent in each of the states is provided, as well as the chart of exact state in each minute of simulation and the chart presenting work periods. Lastly, the cumulative pie chart of state proportions, distribution of states over the simulation minutes on the team level, and chart of the change in the shared mental model are also provided as simulation outputs.

### 4.3 Results analysis

The application of the model is currently limited to the change of inputs (simulation configuration) and analysing the effect of different inputs on simulation outputs. The outputs generated by different simulation configurations can be compared relatively. The impact of a change in simulation inputs can be studied in three main aspects: the impact on project (activity) performance, the impact on agent and team characteristics, and the impact on agent interaction.

Project performance is represented by the time needed to finish activities and the proportion of completed activities during the simulation runtime. Performance is significantly affected by the configuration of simulation inputs (initial setup of agent and project characteristics), but also by the change in characteristics during simulation runtime. For example delays in the start of the activity can result from agent unavailability and unfavourable work periods. Another example is a drop in performance due to insufficient knowledge or skills to start the activity, thus needing to ask and wait for help. Which agents will be requested for help, and how long will it take them to reply also depends on agent characteristics (social competencies, response rate, trust, availability). Furthermore, the speed at which the help is provided depends on the competence difference between agents and the learning ability of the agent that receives help. Because of these dependencies, it is possible to study and compare project performance for different simulation configurations (initial project and agent characteristics).

Agent-based model variables (agent, team and project characteristics) change during simulation runtime. The change in characteristics appears when agents execute different actions (working activities and interaction). Due to the interdependence between characteristics and actions, it can be observed that the change of a particular characteristic indirectly depends on other characteristics at that moment. For example, an agent that has a high knowledge, skills, and social competencies will be repeatedly asked for help by other agents. If the agent responds and helps other agents, their trust will increase and vice versa. Agent's response rate drops once the help is provided so a certain time has to pass until the agent can help someone else. Thus, the configured competencies will affect the dynamics of agent's response rate and the trust of other agents that needed help. This example shows that configuration of simulation inputs has an effect on the change in agent and team characteristics during simulation runtime.

Agent interaction likewise depends on initially configured agent and project characteristics. Agents interact during teamwork activities and when providing or receiving help. As the previous examples show, the amount and direction of interactions between agents are driven by their characteristics. It is thus possible to study how particular simulation configurations (agent characteristics or activity assignment) return different interaction outputs.

## 5. Discussion and conclusion

In the presented initial state, the implemented simulation framework is partially validated. Certain segments of the model are predefined or calibrated with data collected through work sampling study [Skec et al. 2015]. Further data collecting studies and gradual release of predefined segments should be conducted in order to completely validate the model. Nevertheless, it is possible to discuss the applicability and limitations of the model within a current state and within further developments based on the proposed simulation framework.

### 5.1. Model limitations

Since the presented model is in its initial state, it has several limitations. Most of the limitations derive from partial framework implementation. The further implementation relies on studies of development processes and individual and teamwork activity execution and interaction. Once supported by the studies, the remaining segments can be implemented. From the configuration aspect, the model currently supports only partial configuration of competencies, availability, and motivation. Besides the further development of existing inputs configuration, it is necessary to implement roles, experience and behaviour characteristics of agents and selection of different types of projects regarding activities, complexity, and innovation level. Simulation of agent activities and interactions has to be extended regarding detail description of what happens during individual and team activity execution. The current model is limited by prescheduled activities and a lack of activity effect on agent and team characteristics. An additional set of limitations derives from model predefinition. Namely, the model was developed and calibrated based on the results of a two-week work sampling case study. The workflow of each agent and activity duration are predefined. Because of this agents lack freedom when it comes to activity assignment, and activity execution is not driven by model characteristics. As a result, it is difficult to validate the model and compare it to other studies, since it is applicable only to a specific organizational context and for specific project phases. As such, the results are not generally applicable in research and management. Improvements require longitudinal work sampling studies (whole project if possible) in different development environments.

### 5.2 Conclusion and further work

In this paper, an agent-based approach to modelling and simulation of design teams executing development activities is presented. Multiple studies of agent-based modelling of teams in product development are reviewed. Based on these studies and the need for a research and managerial planning tool, a simulation framework is developed. Different framework aspects are briefly described with indications on the supporting literature. An initial version of the agent-based model is developed based on to the proposed framework. A detail description of implemented algorithms will be presented in the future work. In this initial model, it is possible to simulate agents of different characteristics following a predefined workflow of activities. As such, the model is limited regarding flexibility and incompleteness. To develop the model further according to the proposed framework, following goals for further work are identified:

- Introducing activity duration variable that will depend on activity type and agent characteristics such as competencies, experience and motivation.
- Development of an activity manager - an agent that will assign activities to other agents guided by their working periods, availability and competencies.
- Detail modelling of informal and formal teamwork activities. This step should include modelling the duration of activities and interaction of agents, thus affecting change in agent and team characteristics such as trust and motivation.
- Development of several types of workflows that will describe different types of development projects. These workflows should enable simulation of a longer project period and the inclusion of different types of development activities.
- Once the simulation time is prolonged, it is possible to implement permanent knowledge gain when an agent learns and uses knowledge on a regular basis, and knowledge loss when the agent does not use the knowledge.
- It is necessary to develop measuring tools to compare different outputs and enable ranking of different team compositions and workflows.

In addition to listed goals that are of primary interest, the full model realization within the proposed framework requires implementation of agent roles, agent behaviour during activity execution, and the development of an extensive project repository in order to generate workflows of different complexity and innovation level. These framework segments have been elaborated conceptually and require further exploration and development.

### Acknowledgement

This paper reports on work funded by Ministry of Science, Education and Sports of the Republic of Croatia, and Croatian Science Foundation MInMED project (www.minmed.org).

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