Exploring the Advantages of Multi-Method Modelling in the Use Case of a Large Socio-Technical Infrastructure System – The Airport City

Barbara Glock[1], Niki Popper[1], Felix Breitenecker[2]

[1]dwh GmbH, dwh Simulation Services, Neustiftgasse 57-59, Vienna 1070

[2]TU Wien, Institute for Analysis and Scientific Computing, Wiedner Hauptstrasse 8-10, Vienna 1040

barbara.glock@dwh.at

Modelling large socio-technical infrastructure systems tends to be tricky. In the past either one "best fitting" modelling technique was used to model the system or a small part of the system was modelled. This lead to many tradeoffs, where the chosen modelling method got to its limits: by modelling a small part, effects from outside were ignored and modelling the whole system with one method lead to either much detail - where micro-based methods were applied - where it was not required which further lead to high computation times. Using a macro-based approach lead to less detail where it would have been needed. Different parts of the Airport City are modelled with the best fitting modelling technique. These parts are researched for their coupling mechanisms to model the whole system and see how effects in one part evolve and pass to the next subsystem. Currently an agent based model of the landside with a modal split of passenger arrival, a Discrete Events terminal model, a multi-method agent-based model with an integrated System Dynamics model representing the retail area of an airport and an agent based model of the airside are in development and their advantages and disadvantages are being explored.

1 Introduction

The planning of big infrastructure developments is getting more challenging due to more complex structures and an increased number of construction standards. Large infrastructure systems can be decomposed into **subsystems** that are somehow interconnected and correspond on different levels with each other. This makes an analysis more difficult. Furthermore, there are **different views** on the system that need to be addressed and satisfied: stakeholders, planners, consumers, decision makers, etc. On the one side questions addressing profit arise, and on the other side consumers want a specific level of quality. Also ecologic aspects need to be kept in mind. In general this calls for modelling and simulation. These large systems, broken into pieces, consist of different subsystems with much more detail, each of them with its own dynamic effects. This gives an opportunity for **multi-method modelling (MMM)** to use all advantages of each method in combination.

1.1 Related Work

Applying multi-method modelling techniques to model large infrastructure systems hasn't been properly researched yet, since the focus of most modellers has lien in increasing know-how on the singular methods themselves and additionally the computational power hasn't been that advanced in the past then it is nowadays to meet this challenge. Most literature focuses on comparing the available modelling method in their research area to find the best fitting [1] or discuss what the advantages and disadvantages are [2], but also how a model in one paradigm can be transformed into a model of another paradigm [3]. Especially under what circumstances, mathematically described, this is allowed. But, as mentioned before, rather view publications try to combine the advantages of different modelling paradigms: **System Dynamics (SD)**, a rather old approach, developed in the 1950s by Jay W. Forrester [4] has been researched very well [5]. **Discrete Events Simulation (DES)** [6] has been researched very well too. Literature on so-called *hybrid* models, where these two modelling paradigms are being combined, coupling continuous and discrete models, can be found [7]. When it comes to **agent-based modelling (ABM),** this being a rather new approach [8], modellers are still struggling with finding a "right" definition – different definitions exist! [9] -, than thinking of how to combine for example agent-based methods with other modelling paradigms like System Dynamics. Researching literature revealed some works on first attempts and implementations where agent-based models are coupled with System Dynamics models [9] and one paper on a ***classification*** attempt for combining SD and ABM was found [10].

1.2 Aim

The aim of this dissertation project is to research different multi-method modelling techniques for modelling large socio-technical infrastructure systems as airports, to **reveal their advantages and disadvantages** and to **give some guidance on how to apply these different modelling paradigms**. Macro-based and micro-based modelling paradigms are different in view and offer different advantages. *The one modelling method's advantage is the other ones disadvantage. So why not combine their advantages?* The focus will lie on ABM combined with SD and on DES combined with SD, since these two different modelling paradigms are a little bit trickier to combine. The use case where this will be tested is the Airport City, since this is a large, decomposable system and yields a lot of possibilities to apply multi-method modelling techniques.

1.3 Structure of the Paper

In section 2 an overview on the researched modelling techniques will be given. These are System Dynamics, agent-based modelling and Discrete Events Simulation. In section 3 the classification by Swinerd and McNaught of 2012 will be summarized as it is used as starting point for a possible further classification. In section 4 the modelled and partially implemented submodels of the Airport City will be described together with their coupling methods and further planned submodels. Finally in section 5 this paper will conclude with an outlook on further work within this project.

2 Modelling Methods used for MMM

Multi-method modelling with the following three modelling methods are researched and used in the application of airport planning, because these methods are, according to literature, used most often in this area and are also applicable to model the subsystem to answer specific research questions.

2.1 System Dynamics

In this macro-based modelling paradigm the point of view is from above, where only aggregated levels are looked at. It was developed in the 1950s by Jay W. Forrester, who applied it first in management systems [4]. He then transferred this methodology to social systems. Nowadays diverse literature on *System Dynamics* and *Systems Thinking* exists [5]. A SD model consists of six basic elements, as seen in table 1.

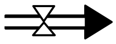
Element	Representation	Description
Stocks (Levels)		describe the state of the system at each time and represent aggregates
Flows		describe the changes of the stocks; are basically auxiliaries and are only allowed between stocks or between stocks and sinks/sources
Parameter		are constants and represent rates on which changes of stocks are dependent
Auxiliary		are helpful for a better understanding of the model and represent algebraic equations
Sink / Source		describe the boundaries of the system
Links		describe the causalities of other elements

Table 1. Basic elements of System Dynamics.

An SD model basically represents a set of differential and algebraic equations. A simple example can be seen in figure 1 and related equations in equations (1) and (2).

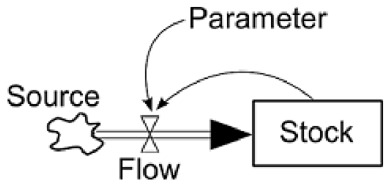


Figure 1. Simple stock and flow structure of SD.

Possible equations for time *t*:

$$\frac{d\,Stock(t)}{dt} = Flow\ (t) \tag{1}$$

$$Flow(t) = Stock(t) \cdot Parameter \tag{2}$$

The dynamics of the system emerge from **causal links** of the modelled variables that often form feedback loops. Such loops can be balancing or reinforcing driving the dynamics of the system.

Application areas are amongst others economics, health care and policy design.

2.2 Agent-based Modelling

Agent-based modelling is a rather new approach and several properties of agents can be found in literature [9]. A selection of those are:

- **Proactiveness, purposefulness**: ability to take the initiative in order to achieve goals
- **Situatedness**: an agent is embedded in its environment and senses and acts on it
- **Reactiveness**, **responsiveness**: ability to react in a timely fashion to changes in the environment
- **Autonomy**: ability to control own actions and internal state
- **Social ability**: ability to interaction and communication with other agent, sometimes even awareness of other agents
- **Anthromorphity**: having human-like attributes like beliefs and intentions
- **Learning**: ability to increase performance over time based on previous experience
- **Mobility**: ability to move around in the simulated physical space, sometimes even between different machines
- **Specific purpose**: designed to accomplish well-defined tasks

Not every agent-based system has all of those properties [9] and depending on the agent's purpose one should not speak of agents and non-agents, but speak of a *continuum of agency*: The more agent characteristics an entity possess and the more developed those are, the higher the degree of agency it has.

2.3 Discrete Events Simulation

Discrete Events Simulation models are similar to agents, but the entity modelled here is not like an agent autonomous. It is passively led through the system instead. Furthermore, changes in the state of the system happen due to events at discrete points in time [11]. Between two consecutive events the state remains unchanged.

Basic elements of DES are:

- **Entities**: have discrete properties and can be arranged in sets or lists
- **Events**: is an instantaneous happening that changes the state of the system. Events are arranged in an event list and are scheduled by using event notices that provide different information like type or time of event.
- The **clock**: is a global variable that represents the simulated time. There are activities (time spans of certain length already know by simulation start) and delays (time spans of uncertain length like waiting time of a passenger in a queue). The clock can be forwarded in different manners.
- **Scheduler**: handles the event list, forwards the events to the event processing routine, also re-schedules events if necessary and updates the clock.

This kind of modelling is mostly used in logistics and transportation.

3 Classification of MMM

Researching literature revealed that few attempts in multi-method modelling were done, but only one paper was found that tried to classify models that used ABM and SD modelling to model the whole system. There are three proposed categories [10].

Two coupled submodels are called **interfaced** if they have some point of interaction like communication between elements. The submodels run **alternating and independently** (see figure 2). There is no direct feedback between the submodels.

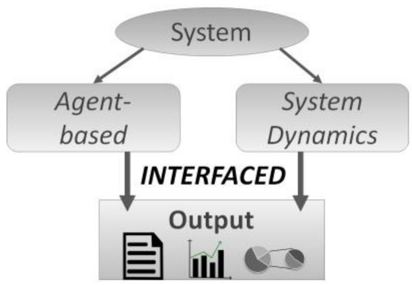


Figure 2. Interfaced multi-method model.

Two submodels are **sequential** if one submodel needs the output of another as input (see figure 3).

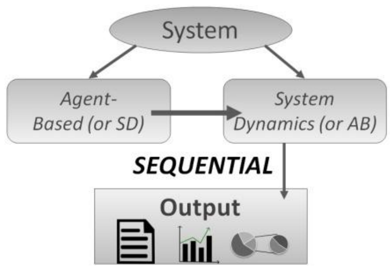


Figure 3. Sequential multi-method model.

In an **integrated** multi-method model the submodels interact with each other in some way, as can be seen in figure 4.

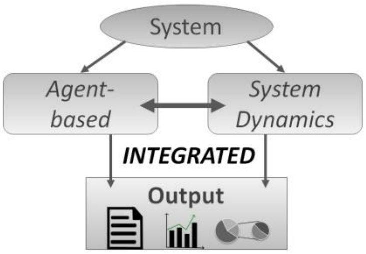


Figure 4. Integrated multi-method model.

According to Swinerd and McNaught [10] there are three ways to model an integrated design:

- **Agents with rich internal structure**: within each agent an SD model exists (see model on retail area). One can think of the SD model within an agent as the agent's "brain" that "tells" him what to do in a dynamic way. Here, influences from both sides can be considered: ABM submodel passes information to the SD submodel and vice versa.
- **Stocked agents**: a level within an SD model is used to bind an aggregate measure of an agent-based model. This could be an SD submodel that calculates production costs on car sales and the influence of fuel price on consumer choice of vehicle technology where consumers are modelled in the AB submodel. Here only influences from SD to ABM are modelled, but not the other way round.
- **Parameters with emergent behaviour**: a parameter of an SD model is calculated by an agent-based model. An example is an agent-based submodel where demographic development is modelled with agents together with their individual properties (age, sex, maybe socio-economic factors). Out of these properties the value of a parameter for a coupled SD submodel is calculated.

There is a fine line between the classes of multi-method models. The modeller has to decide what fits best. It is also dependent on where the system boundaries lie. This classification approach is very useful as a starting point in researching multi-method modelling, since it is also applicable not only for SD and ABM modelling but also for other modelling methods.

4 Use Case: Airport City

The Airport City gives a good example of a **large socio-technical infrastructure system** to model, since on the one hand passenger demand forecasts predict an increase in the long term growth of transported passengers of avg. 4% per year [12] and on the other hand the system can be decomposed to smaller subsystems, that are somehow interconnected to each other on different levels. In figure 5 a selection of important areas of the Airport City can be seen.

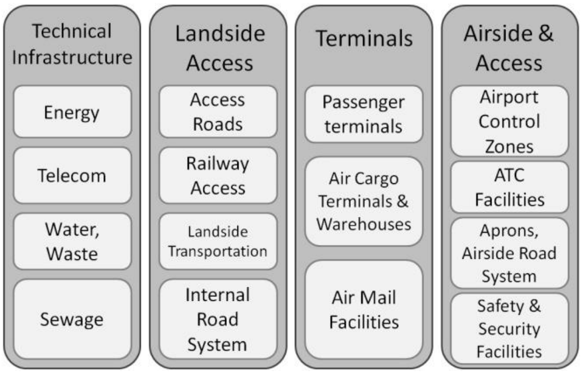


Figure 5. Selection of areas in the Airport City. (Source: adapted from company *AI-MS Aviation Infrastructure Management Systems*)

Also different views need to be satisfied here as well: planners, consumers, and stakeholders. Currently, a terminal model modelled with Discrete Events and a model of the retail area as an integrated ABM-SD model with *rich internal structure* have been developed. Furthermore, in development are an agent-based model of the landside and the integration of a network-based agent-based model of the airside. Still planned is a SD model to calculate costs/profit and CO2 emission of airplanes. The advantages and disadvantages together with the possible coupling mechanisms are being researched. The described models are implemented in AnyLogic 7 [13].

4.1 Terminal Model with Discrete Events

The terminal area is after the landside area the second area where departing passengers go to. The processes going on include check-in, security controls, passport controls and proceed to gate through retail area [14]. These processes are dependent on specific features of the passenger, like if he is business or tourist passenger (only hand luggage or not), or what his destination is (if within Schengen the passenger can proceed without passport control) or if he is handicapped or not. This submodel also includes transfer passengers, meaning passengers arriving at the airport by plane, going through passport control if necessary and proceeding to gate after going through retail area. This circumstance shows on the one hand, that this submodel gets input from the landside as well as from the airside and if some delays or other effects happen in the parts of the airport not represented in the terminal submodel it has an effect on the terminal submodel.

The research question in this model is if resources like personnel and number of open counters is enough at each time to maintain the quality standards measured in waiting time of passengers. This being a simple server-queue question is modeled best using Discrete Events with counters and personnel being resources and passengers being entities.

A first version of a DES model has already been implemented, as seen in figure 6. This model includes the basic servers in such a process (check-in, security, passport control and transfer) and distinguishes between tourist and business passengers. In AnyLogic simple blocks for creating (sources), processing (server), and queuing (queue) entities are used. Resources are created via a (scheduled) resource pool. Here, sources and sinks (Exit) build the interface to an adjacent submodel where entities are led through the system.

An agent based model modelling the landside can be coupled by this rule: every time an agent (passenger) exits the landside model, an entity (it is possible to pass other information as well) in the DES model is generated. On the other side the exit can be seen as an interface as well. Passengers proceed to the gate through the retail area. Every time an entity enters the sink in the DES model an agent will be created in the ABM model of the retail area. This connection is from type interfaced.

4.2 Retail Area with Integrated ABM - SD Model

The retail area is economically seen a very important part of the airport since most of the profit is gained here. The retail area is a shopping area after having passed the controls in the terminal where passengers go through when they proceed to the gate to depart. One main research question in this area is to maximize profit by guaranteeing a specific level of quality for passengers like a short way to the gate or attractive sales. Here also spatial information is needed.

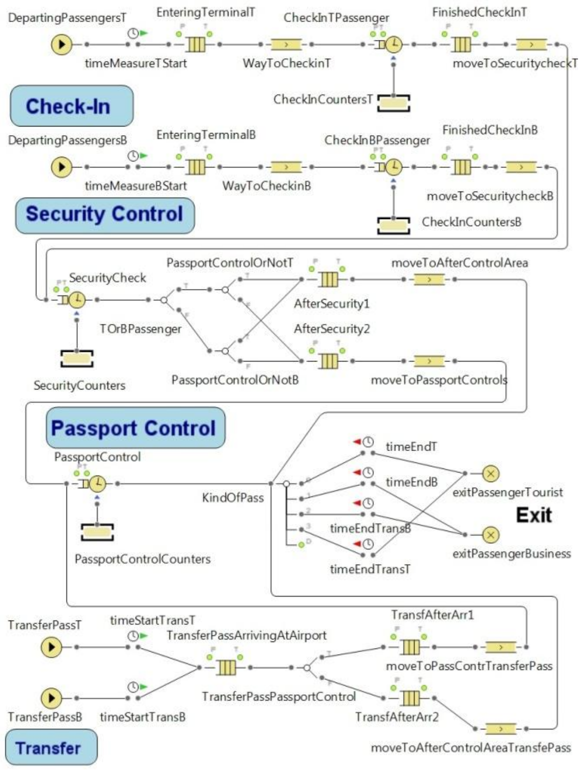


Figure 6. Discrete Event Simulation of the terminal.

The processes are dependent on an individual's behaviour: he/she reacts to the environment and other passengers; therefore an ABM submodel that includes spatial information (map of the shops) is used. The environment is the retail area with the shops. The inner parts of an agent should be dynamically changing, since this is more realistic: next to some individual parameters, the agent consists of an SD submodel that models the need to eat and the need to buy other things. In this case the retail area submodel is itself an **integrated model of agents with rich internal structure**. Each agent follows rules like:

- proceed to gate in time
- if hungry and still time to departure, then look for eating store and eat
- in dependence of attractiveness of store and in dependence of estimated income buy something if there is still time to departure and the need to buy something exceeds a specific threshold

These rules always take into account the by the SD model calculated *need* to buy something. This means there is communication from the SD module to the agent based module (tell him where to go). In return the need is dynamically calculated by the SD module by using individual information from the agent (age, gender, time until departure), but also using information from the environment of the AB module, like the attractiveness of the store that has some "basic attractiveness" and furthermore is calculated by the number of people inside (if no people are inside it may be something wrong with it, if too much people are inside it is overcrowded).

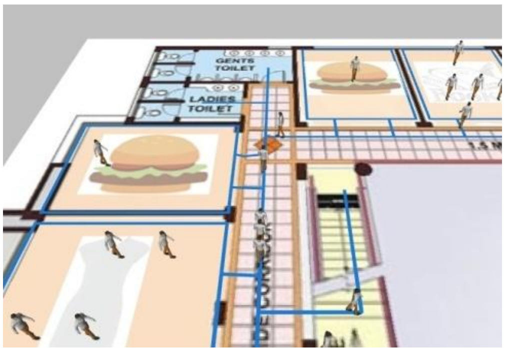


Figure 7. Integrated multi-method model of retail area - agents with rich internal structure (agents).

A first version of this submodel has been developed (by M. Obermair and B. Glock), as seen in the 3D version of the animation in figure 7. A network is applied to a ground floor and passenger agents interact on this plan with the shops trying to satisfy their goals that are modelled with SD, which can be seen in figure 8.

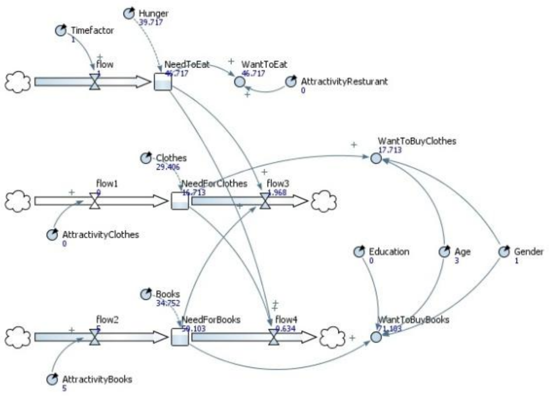


Figure 8. Integrated multi-method model of retail area - agents with rich internal structure (SD model within each agent).

Clearly, this multi-method approach allows agents to develop their needs dynamically and not by discrete rules, which gives a more realistic picture of the world.

4.3 Airside

The airside of the airport is the part where diverse processes take place that deal with outgoing and incoming planes, like it is shown in figure 9.

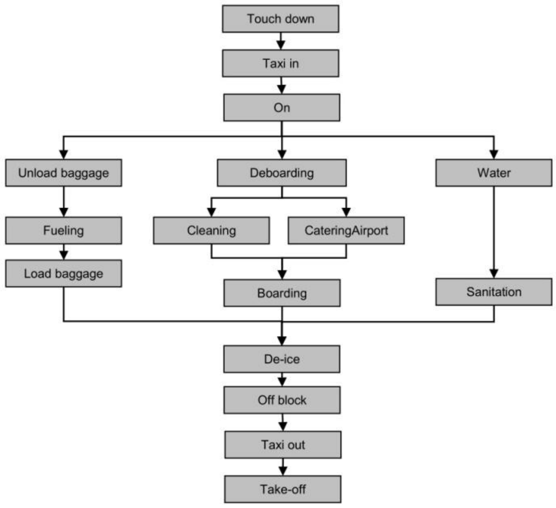


Figure 9: Ground handling process [15].

The so called **ground handling processes** include all processes around the plane. After touchdown (landing of the plane), the taxi arrives to get the passengers. After that the unloading and water refill starts. There are some limitations like cleaning and catering have to start after disembarking or fuelling after unloading luggage that need to be considered as well. In this submodel the spatial context plays an important role since travelling times contribute to quality measurements for passengers and the calculation of optimizations regarding the ground handling process itself. The amount of flights is increasing and space on the airside where passengers can board (directly through the gate vie boarding bridges or on the apron) is limited. Therefore, in this case an **AB submodel** is used with a given **network** on which the agents can operate, as seen in figure 10.

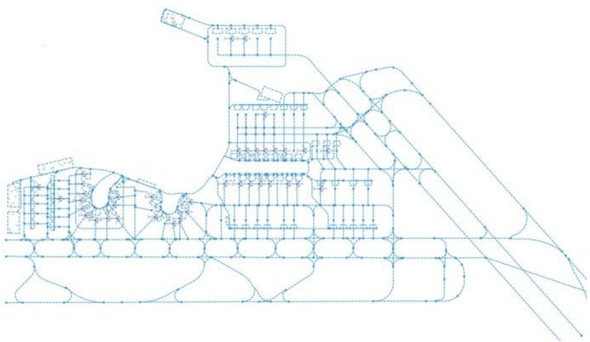


Figure 10: Example of an airside network of the Vienna International Airport.

Different types of agents interact with each other on an environment like the network (selection):

- Planes
- Mobile stairs
- Catering vehicle
- Belt loader
- Baggage cart
- Container/pallet dolly
- Container loader
- Tractor, ...

They have one overall goal to get the plane as soon as possible up in the air again.

4.4 Further Planned Submodels

Next a submodel modelling the landside with agents where the type of agents is different (cars, and not passengers) is planned and a submodel modelling the CO2 emission (with SD) as an integrated design is planned, where the agent-based and Discrete Event submodels have an influence on parameters of the SD model (classification of parameters with emergent behaviour).

So, also questions addressing different types of agents and their coupling mechanisms can be addressed as well as questions regarding the coupling of those two modelling paradigms the other way round: in the retail area an overall agent-based model existed with an SD model integrated and here an SD model acts as overall model with agents having an influence on this parameters.

4.5 The Big Modelling Picture

Summarizing the proposed submodels as seen in figure 11 there is a terminal submodel with DES that interacts with the retail area submodel modelled with ABM, which itself is a multi-method model as the "brain" of each agent is a SD model. The retail area submodel will be connected to the airside submodel. A submodel of the landside will be integrated. Passengers proceed not online from landside to the airside, but also from airside to the landside, if arriving. Transfer passengers are included as well. So, we can see that those submodels are from integrated form all along, because these submodels have to exchange information (e.g. the agent or entity being passed on) as well. The further planned SD submodel, calculating profit and CO2 emission requires information from the other submodels. Somehow, this SD model will give (delayed) some information back to the submodels (dotted lines), since the effect of the CO2 development will have an effect on the structures of the airport implemented with the submodels.

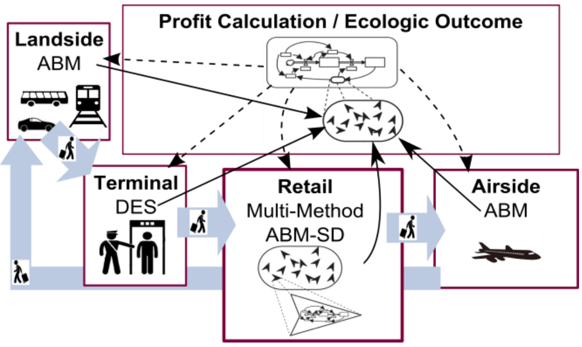


Figure 11: The coupling schema of the modelled and planned submodels

The advantages of this multi-method modelling technique clearly are that the model gets more realistic by also including individual's properties. The disadvantage is that it gets more complex. On the other hand due to the modular architecture verification and validation will be, compared to a whole ABM model, a little bit easier.

5 Conclusion and Outlook

Using multi-method models is getting more and more important [16], since large infrastructure systems like airports get more complex and larger. Errors by using only one method for the large system can accumulate over time resulting in difficult decision making. By using different (best fitting) modelling methods for different subsystems and utilizing all their advantages a more realistic presentation of the model can be created. This also makes communication to decision makers easier and accumulating errors are eliminated to some extent. Furthermore, calculation times of the simulation models can be reduced as well.

Next (interesting) steps in this project include building and integrating a CO2-emission submodel and a profit calculation model that interact with the former described submodels and an airside and a landside model.

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