The Digital Twin concept and its role in reducing uncertainty in synchromodal transport

Tomas Ambra[1,2,3], An Caris[2], Cathy Macharis[1]

1. Vrije Universiteit Brussel, MOBI research center, Brussels, Belgium
2. Hasselt University, Logistics research group, Diepenbeek, Belgium
3. Research Foundation Flanders (FWO), Brussels, Belgium

Corresponding author: tomas.ambra@vub.be

Abstract: *Transparency and information exchange are important parts of synchromodality that contribute to better overview of options when tackling delays, dynamic switching, and handling of unexpected events that affect delivery lead-times and costs. The most challenging aspect when making decisions in a complex adaptive dynamic system, is the ever-changing environment as we introduce more flexibility which may lead to more unpredictable outcomes. This paper presents 2 simple illustrative cases to asses different transparency levels and the adaptive behavior of assets; 1) a static case where assets do not have the ability to respond proactively to disruptive events, and 2) a dynamic case where assets have the ability to query their environmental context and exchange information. The severity of the events is captured by probability distribution functions by deploying Monte Carlo simulations to showcase the potential benefits of the Digital Twin concept in a synchromodal context. The links between current Digital Twin applications and synchromodal transport are discussed in order to spark a new wave of reducing uncertainties in dynamic environments. Lastly, the paper sheds more light on how to connect closed virtual simulations with the real physical system.*

Keywords: *Digital Twin, Synchromodality, Uncertainty, Monte Carlo, Simulation, GIS, agent-based modeling*

1 Introduction

Synchromodal transport presents an extension of intermodal transport, which is a combination of two or more modes in one integrated journey with standardized loading units, by introducing more flexibility and transparency to facilitate dynamic re-routing and modal switching in near to real-time (Ambra et al., 2019b). Synchromodality can be thus perceived as real-time, dynamic and optimized intermodal transport. Given its real-time dynamics and flexible nature, different actors and transport modalities need to work together and adapt according to unexpected events as well as contextual information that affect transport processes. These events and contextual information can be positive or negative perturbations that shape freight movement and transport mode selection, such as newly incoming orders, transport delays, cancellations, collaborative bundling opportunities, accidents, water levels, strikes and many more. However, real-time mode selection requires involvement of extra parties in the process to solve transparency issues as to who has the cargo and where it is located. Crucial elements in this regard are situational awareness of the current system state and projections of how the system will evolve once different actors take different actions. While there already exist real-time control towers (ESRI geo-event server, MPO, ActiveViam etc.), and data fetching/scrapping tools (Webhouse.io, VisualScrapper, Spinn3r etc) that have the ability to integrate data via JSON at a single reference point, these applications provide past and present positions of assets and trends. In this paper we depart from the past and present assets' states and focus on how future problems could be mitigated and emerging opportunities utilized if there is a possibility to speed-forward into the future. In order to estimate where assets (barges, trains and trucks) will be in 2, 3 or 5 hours based on congestions levels and infrastructural developments, and which terminals, distribution centers and other moving assets will be in their vicinity, is a challenging task. To acquire such future states of assets, one would need a time-machine to travel into the future, observe how the future looks and then return back to present time to make a decision. A time-machine will mostly likely not be developed yet, but the rather new digital twin concept might come close to this metaphor.

The digital twin concept is the latest wave in simulation technology as it uses simulation models to project possible behavior(s) of the real system. Simulation technology's inception is dated around the 60s when simulation was limited to a small range of individual topics such as mechanics, when in the 80s it was used in fluid dynamics and other engineering designs. Starting from the year of 2000, simulation allowed for multilevel and multidisciplinary system approaches to test and assess overall system designs, and from 2015 onward, simulation has formed the core of the digital twin concept by providing seamless assistance along different tasks and processes with direct connection to operation data (Boschert & Rosen, 2016). Gartner claims that digital twins will be adapted by half of large companies who will consequently gain a 10% improvement in effectiveness (Pettey, 2017). Hence, the concept is receiving more attention, but it has never or rarely been considered in the synchromodal context. In the following section, the digital twin concept and its current applications are reviewed in order to understand what it is, but also what it can become. As this paper addresses the adaptive nature of synchromodality, we pose 2 research questions: (1) Is synchromodal dynamic switching and re-routing always a better solution? (2) How can the digital twin concept/technology reduce uncertainties? The objective of our work is to deepen the understanding of digital twins and their potential use in synchromodal transport. The paper is structured as follow: section 2 reviews the digital twin concept and its use, section 3 presents the methodological approach where we describe our experimental design as well as the benefits of simulation, and section 4 describes the experimental results together with the potential role of digital twins in connecting virtual simulations with real physical environments. Concluding remarks are presented in section 5.

2 Literature review

The Digital Twin (DT) term itself was introduced to the broad public by NASA in its technology roadmap for modelling, simulation, information technology and processing where the DT is defined as "an integrated multi-physics, multi-scale probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin" (Shafto et al., 2012). Since then, the term has been altered and also challenged by different authors. Boschert and Rosen (2016) perceive it as a description of a component, product or a system that evolves with the real system. Grieves and Vickers (2017) define it as a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. According to Alam and El Saddik (2017), the DT is "an exact cyber copy of a physical system that truly represents all of its functionalities". Zheng et al. (2019) term the DT as "an integrated system that can simulate, monitor calculate, regulate, and control the system status and process".

However, Batty (2018) perceives the DT as a cliché and states that a computer model can never represent a DT as many physical elements of the real system are ignored. While Batty's argument is valid, one should also consider the necessary abstraction levels needed to build a credible enough model to capture the simulated phenomena sufficiently. This is to say that "boiling the ocean" will not yield added value in many simulation models. Digital simulation models for freight transport will not require to model detailed physical processes at the micro level for routing strategies and estimated time of arrival (ETA) calculations. In fact, Batty (2018) himself concludes that bringing the digital model closer to reality is rational when building computer models. A DT is not a mere detached virtual representation of a physical twin, but rather a living organisms that interacts with its physical twin via sensors and receivers connected through the Internet of things (IoT). Even though there are other terms which depict the notion of physical and digital objects interacting on a continuous basis such as the digital mirror model, digital reflection, avatar or a digital shadow (Erikstad, 2017), the DT term appears to be adapted by most of the authors in their applications.

With regard to the existing applications, Brenner and Hummel (2017) have developed a digital shop floor management system based on the DT notion. A three-dimensional DT is devised by Knapp et al. (2017) in manufacturing to predict variables affecting metallurgical structures. However, the digital representation is not connected to its physical counterpart via sensors and the DT notion does not clearly correlate with the earlier definitions.
Schleich et al. (2017) propose a simple reference model for DT in product design and manufacturing. In the work of Söderberg et al. (2017), the DT is referred to as a simulation for real-time control and optimization of products and production systems, where the authors specify data models to move from mass to a more individualized production. Alam and El Saddik (2017) develop a driver assistance application where the DT is to identify various driving events and provide recommendations for drivers, insurance companies and emergency units. Uhlemann et al. (2017) introduce a learning factory based on the DT to demonstrate its benefits and familiarize the workers with new technologies and their implementation. Tao et al. (2018) focus on how to generate and converge cyber-physical data and apply their framework in three cases that relate to product design, product manufacturing and product service. Lastly, Zheng et al. (2019) apply the DT to model a welding production line.

The digital twin concept has been so far applied to manufacturing, shop floor management and product engineering designs of artefacts/objects. As the scope of current research is confined to 4-wall environments and products, our work will take the DT concept to the next level by exploring its potential use outside of the 4-wall environments and object designs, by adapting the concept to synchromodal freight transport processes and movements of assets in geographic space by using Geographic Information Systems (GIS) and agent-based modelling (ABM). As all the reviewed applications are at their infancy, our paper does not provide a ready-to use DT model for synchromodality, but it rather explores its potential use for synchromodal transport. Synchromodality/Synchromodal transport is to support optimal integration of different transport modes and infrastructure in order to induce a modal shift from road to inland waterways and rail by making the modal options, and synchronization of orders and available capacities, more dynamic, flexible and acceptable. A review of the synchromodal concept and its applications has been done explicitly by Ambra et al. (2019b) which is why we refer the reader to their work for a more detail overview. We depart from the notion of synchromodality depicted earlier in the introduction.

3 Methodology

A high-level methodological approach is proposed in this section to reap the potential benefits of the DT concept. The theoretical basis of this paper rests on the notion that the DT relates to a living dynamic simulation environment that mimics the real physical system by continuously updating its virtual environment in order to provide support to certain tasks and evaluate most probable implications. In fact, the digital virtual environment exists in parallel with the real system and updates itself through sensors based on specified intervals and/or events. Nevertheless, it is rather vague whether the DT should be perceived as an object or technology. The latter refers to a simulation method/approach to modelling and connecting virtual and physical environments. To clearly distinguish entities and concepts in this paper, the DT is perceived as a technology (DTT; Digital Twin Technology) that connects the Physical Twin (PT) with its Digital Twin (DT). The DT is a digital instance of the physical object. The DT exists in a Digital Twin Environment (DTE) also introduced by Grieves and Vickers (2017). In the following subsection, the DTE will be discussed as well as its agent-based components that can act as DTs once connected to real PT's. The PTs represent assets such as barges, truck, trains, vans and parcels that may send and intercept message via sensors and receivers.

3.1 The role of simulation in data-centric and process-centric realms

To understand how DTT can improve current decision making processes, the role of simulations and its relevance is addressed first. Mathematical and data-centric models (machine learning models) are able to learn from past outcomes, predictions and errors. However, relying purely on mathematical and data-centric models for decision making in complex systems is risky as they are limited to forecasting and assessing effects of events in the aftermath; meaning that a similar event must have occurred historically and this effect is known at present. The challenge comes when the system is exposed to previously unexperienced or unseen events (Figure 1 red). An example of such an unexpected development outside of historical bounds is/was the Randstat case within the Rhine-Alpine corridor where a sinkhole in a tunnel caused unprecedented train disruptions; no mitigation schemes had been available for shifting to inland-waterways or other service providers. The disruption effect nearly froze operations of HUPAC for weeks. In this regard, computational/simulation models can reinforce data-centric models by offering process-centric approaches.

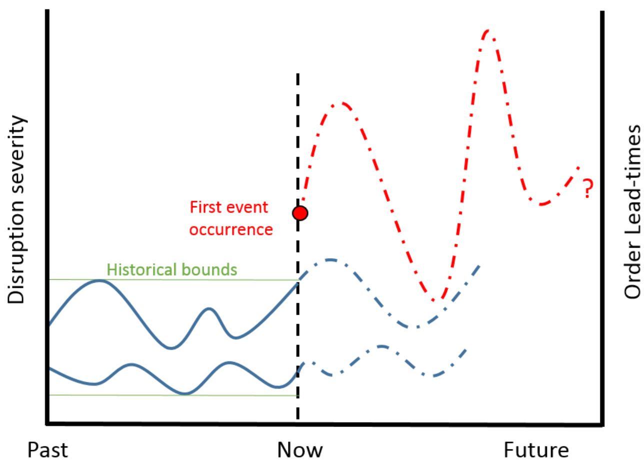

Figure 1: Theoretical illustration of an event that never occurred within the experienced historical bounds, and its potential consequences. The lines depict lead-times of orders when exposed to disruption.

The less data is available for an analysis, the more added value a simulation can provide. In an event for which there is no data, or the phenomena under study do not exist, simulation can generate a vast amount of data and execute model runs outside of historical bounds. Simulation works best when business processes are well understood, the preferences clearly stated and the fidelity of physics well mimicked. The latter refers to barge arrival calculations based on water levels, depth, currents, weather conditions, engine type, load factors and upstream/downstream direction. Similar rules apply to truck movements that are affected by congestions levels, road type and its layout as well as trains that share the railway infrastructure with passenger trains. On the other hand, mathematical and data-centric models can help simulations by using data driven approximations to reflect on processes more accurately and better inform simulation models where behavioral processes are hard to identify.

Mathematical and data-centric approaches are powerful as long as the studied system does not contain complex interdependencies and consecutive events that require spatial and temporal awareness. By means of simulation, business rules and objectives will determine the evolving system when projecting into the future, as these rules will mimic how businesses act over time. Pure analytical solutions are goal seeking and lack decentralized biases that exist in reality which is why they may not capture counterintuitive elements as good as simulation does; things one would never think about once entities start affecting each other. The DTT can mimic the physical system through virtual reality by making use of GIS for better spatial intelligence, agent-based models for decentralized local behaviors of entities such as transport means, and discrete event models for process-centric logic in terminals and other 4-wall environments.

3.2 Experimental design

The essence of the DTT for synchromodal freight transport is in representing space via Geographic Information Systems (GIS) that have the ability to mimic real-world environments and entities. GIS should thus form the Digital Twin Environment (DTE); the cornerstone of the DTT where entities (DTs) may learn how to react and adapt to seen and unforeseen events. A fine-grained DTE will also contribute to more detailed external cost calculations as the real cost of transport goes beyond the immediate internal costs related to transport and logistics operations. There is a wide variety of externalities such as congestion, accidents, noise, air pollution, loss of space, infrastructure damage and the impact of up and downstream processes which create additional burdens for society and ameliorate climate change.

The main modelling canvas that will serve as the DTE is a digital map that comprises of road, rail and iww vector files. The vector files, also called shapefiles, are acquired from ETISplus which is the European Transport policy Information System, and Eurogeographics. The vector data files contain the TEN-T networks for roads, railways, airports, ports and the watercourse system identified by Directorate-General for Mobility and Transport (DG MOVE). As indicated in Figure 2 the cyan colored polylines represent navigable iww and yellow lines represent railway freight priority links. The other dark image on the right depicts all geocoded locations of European ports and inland terminals. Each location contains attributes with regard to mode switching possibilities and terminal size. The GIS environment presented herein provides agents (digital objects) with real-world locations based on the WGS84 geographic coordinate system, having Greenwich (0, 0) as its prime meridian. As the WGS84 coordinate system is used as a reference system by GPS, Google Maps as well as by Microsoft in its Bing Maps, it represents a good base for mirroring the real physical world and physical assets since these assets are governed by a such geo-referenced system already.

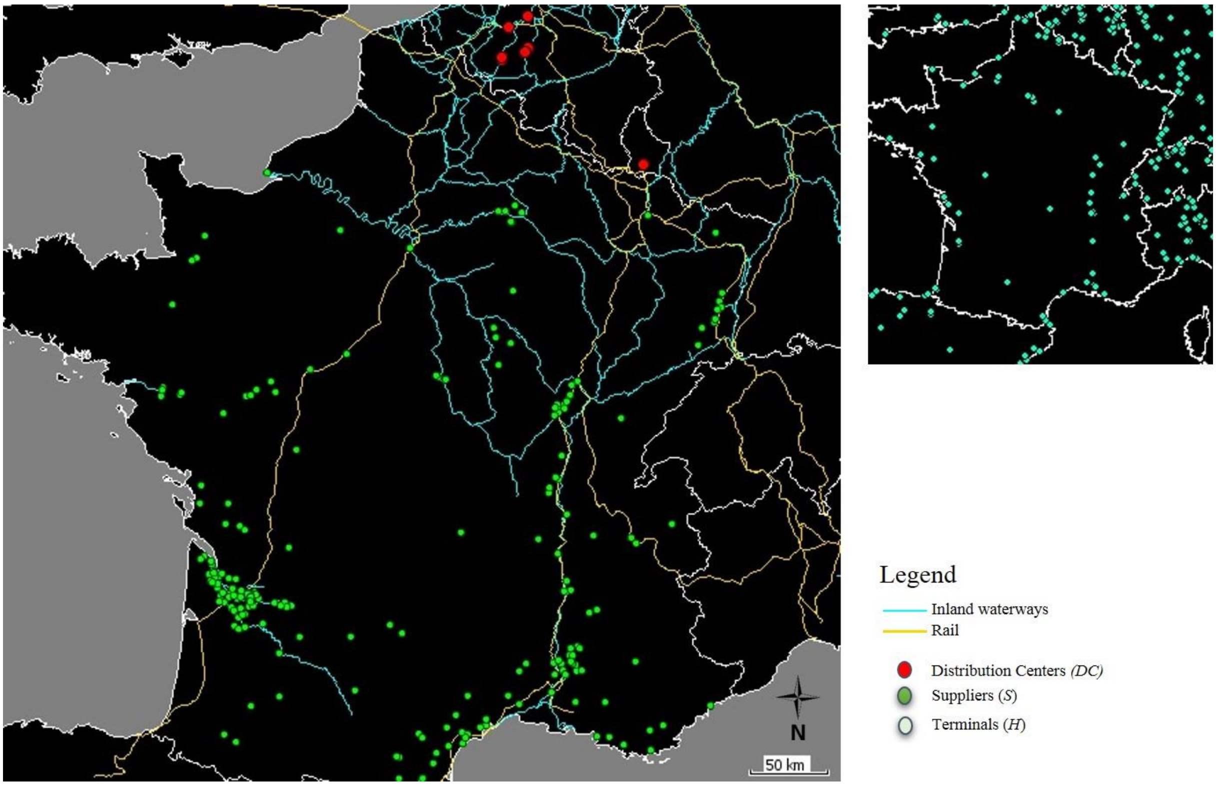

Figure 2: The left image illustrates our study area depicting 220 origins (S), six destinations (DC) and 325 terminals (H). Road shapefiles were excluded for visual clarity. The right image represents all European terminals

The experimental design is a shortened version of Ambra et al. (2019a). We start with an initial solution that refers to orders being transported from green supplier locations (*S*) to red distributions centers (*DCs*). Figure 2 depicts these origins and destinations. The flows represent intermodal journeys where trucks collect orders at *S* locations and depart to the nearest terminal (*H*). The main leg is carried out via inland waterways or rail, until the next unloading terminal where the order/container is transshipped on a truck which delivers the order to its corresponding (*DC*). Figure 3 illustrates such and intermodal journey to which we will refer to as the freight system. The system contains multiple similar intermodal stretches in parallel due to the fragmented spatial context of the orders' origins as well as destinations. This system will be exposed to perturbations to assess its reconfiguration/resilience.

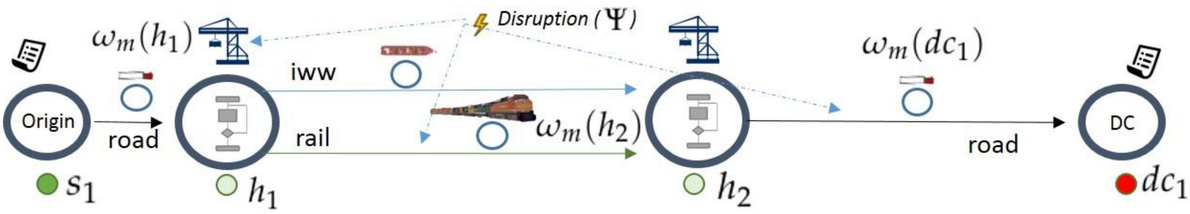

Figure 3: A visual example of an intermodal delivery indicating how Ψ disruptions affecting agents in ωm(.) transition state.

The trucks, trains, barges, orders and terminals are represented as agents. The agents have the ability to self-organize locally which may lead to significant reconfiguration of relationships and processes based on internal perturbations or external shocks (Bak, 1996). Agents can process and exchange information with other agents as well as perceive other entities, obstacles or sense their surroundings. Given the decentralized nature of agents, their ongoing delivery processes may reconfigure depending on the geographical location of the disruption, without unnecessarily bothering other agents and their ongoing processes. In this paper the agent reconfiguration is tested by imposing disruptions upon them. We consider disruptions Ψ in a form of three disruption profiles (Table 1). Profile 1 (Ψ1) is applicable to road only, to simulate the overall delivery performance of intermodal orders if a truck agent arrives late, or not- depending on how far the individual trucks are from terminals. We assume that these disruptions, slightly more severe than daily congestion, last 1–3 h. Profiles 2 (Ψ2) and 3 (Ψ3) last 3-6 hours and 1-3 days respectively. Iww accident data were not available, which is why this study was limited to mainly rail disruptions. The disruption duration is linked to uniform distribution functions which determine the length with each new disruption occurrence. Many model realizations with Monte Carlo simulations are carried out to approximate the stochastic probability distributions; during each realization the model draws a different value from the probability range depicted by the uniform distribution functions.

Table 1: Disruption profiles and their severity

Ψ	Description (*Example)*	Probability of occurrence per year	Duration
1	**Frequent and short** (Delays caused by detours, blockages, light accidents, road works, etc.)	30% - 40%	Uniform (1, 3) h
2	**Less frequent and short** (Breakdowns, maintenance, moderate weather conditions, trees on rails etc.)	6% - 9%	Uniform (3, 6) h
3	**Less frequent and mid-long** (Strikes, severe weather conditions, floods, train collision, derailment etc.)	6% - 9%	Uniform (1, 3) d

The simulations cover 1 year and are based on order requests acquired from a retailer in Belgium. Order placement starts when the real-time simulator enters a new week. When the simulator enters week 3 for instance, all order requests that correspond to week three will be sent out to their S locations. Starting from the initial solution displayed in Figure 4, disruption profiles are deployed to stress-test the system resilience to perturbations. Two simulations are compared; S1 represents the intermodal static solutions and S2 the synchromodal dynamic solutions.

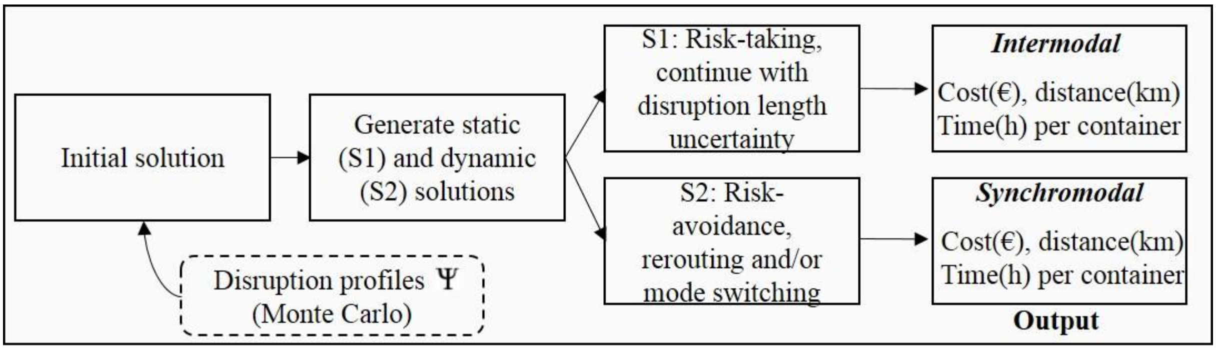

Figure 4: Schematic overview of the short experimental design

The former, S1, is labelled as risk-taking which means that once the disruption profiles Ψ from Table 1 are applied, all the agents in transition state ωm (.) will be exposed to delays caused by Ψ given their current geolocations in space and time at the moment of occurrence (Figure 3). The entity inside the (.) expression in the ωm state indicates the destination towards which the agent is headed. In the static case (S1) the agents are delayed without knowing the disruption length. The latter, dynamic (S2), means that agents receive information about each disruption and proactively seek alternatives, labelled as risk-avoidance. Planning is done as late as possible so that the planners have enough time to detect disturbances and respond to them proactively. For profile 2, the trains will be able traverse a path in case of terminal breakdown. This may result in re-routing where the truck agent will move to the next nearest terminal. A search radius of 300 km is added to query iww terminals first. This was to find potentially cheaper options and also avoid trucks seeking rail terminals further inland in the opposite direction. The radius applied to orders situated within the Rhine–Alpine corridor which are closer to Basel in Switzerland. For longer-term disruptions in profile 3 such as rail strike, the LSP will seek other than rail alternatives, such as inland waterway transport.

Information regarding calibration and validation as well as more detailed simulation descriptions and pseudocodes can be found in Ambra et al. (2019a). Let us recall that we re-use a simplified version of the authors' original case, and herein provide an additional DTT dimension to introduce a first step towards synchromodal DTT.

4 Results and discussion

The results of the experimental design are described and discussed as first, to show how notifications in a transparent network can contribute to freight transport processes in disrupted settings. The second part of the section is devoted to the DTT for synchromodality.

4.1 Intermodal and synchromodal result comparison

This subsection is to answer our first research question (*Is synchromodal dynamic switching and re-routing always a better solution?).* The results concern individual orders after reaching their final distribution center. Each dot in Figure 5 represents a single order for simulation 1 (red) and simulation 2 (green) plotted on axes representing its cost and lead-time. It can be inferred that some green orders incurred slightly higher costs due to longer distances. This development can be attributed to the pro-activeness of agents that seek other available terminals in the synchromodal case (green) once the disruption event is imposed. The most visual outliers are between 60 and 66 h which can be explained by the risk-avoiding approach of synchromodality choosing terminals further away and incurring delays by unnecessary detours. A cost decrease is observed between 45 and 50 h for green synchromodal dots where choosing barge services located closer to the order's final destination yielded lower costs as compared to the red intermodal dots above them.

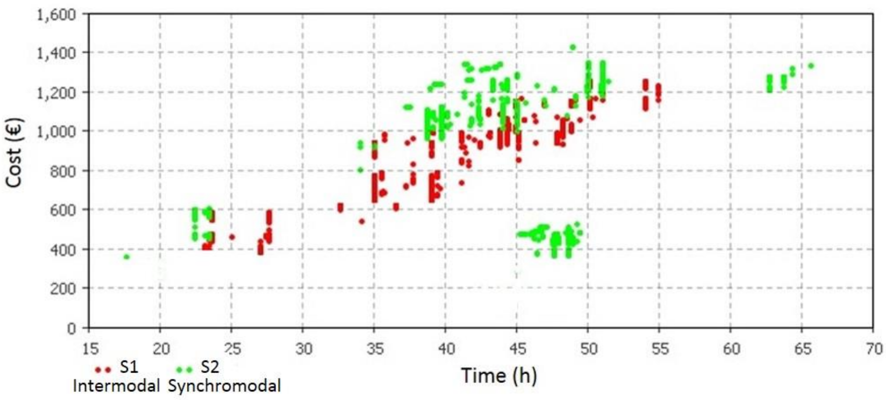

Figure 5: Comparison of order delivery performances after exposing simulation 1 and 2 (S1 and S2) to disruption profile Ψ2 for static intermodal (red) and dynamic synchromodal (green) solutions.

Both simulations are stochastic as they work with random numbers generated by the disruption profiles. The S1 and S2 are executed with the random seed being fixed in order to reproduce comparable simulations. This is to ensure the same sequence of random numbers is drawn from the uniform distribution functions that represent our disruption profiles. However, disruption profile Ψ2 may assign a delay of 3.5 h to orders from week 1 and 5.5 h to orders in week 2, which in fact means that orders from week 1 are not exposed to 5.5 hour delays. Such a sensitivity analysis of the disruption profiles is shown in Figure 6 and Figure 8 (for profile Ψ3) by executing 100 replications of S1 and S2 simulations under profile Ψ2.

The colored areas in Figure 6 represent envelopes for each time “slice”. These can be perceived as extended box-plots where the envelope coloration shows quartile intervals. The darker the color, the more percent of orders accumulated in the given area when replicated for different delay inputs. Such an overview of order delivery fluctuations provides a better visual understanding of the stochastic uncertainty embodied in our model.

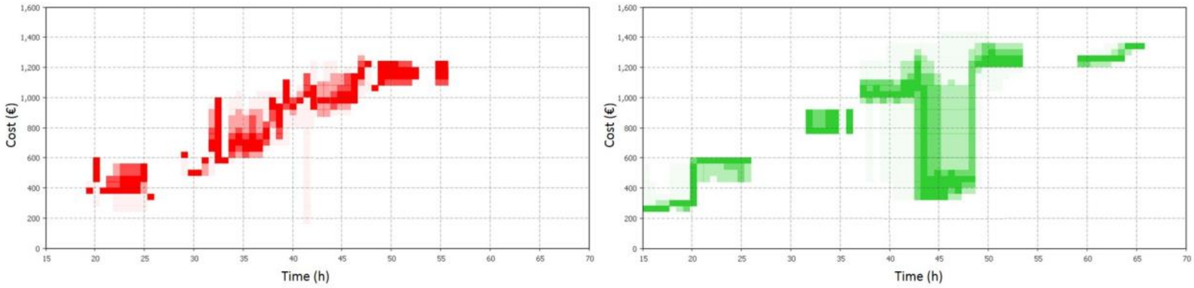

Figure 6: Monte Carlo experiments related to Figure 5 with disruption profile Ψ2 for static intermodal (S1 red) and dynamic synchromodal (S2 green).

After exposing S1 and S2 to disruption profile Ψ3 (Figure 7), the proactiveness of synchromodality (green) yields significantly better performance in terms of costs and lead-times. This development was caused by the fact that all truck agents search iww solutions as the usage of rail is omitted. In this case the geo-spatial search went beyond the 300 km radius, ignoring several rail terminal options that lay in between, until the nearest iww terminal was found. In comparison with the less severe disruptions under profile Ψ2 (Figure 5 vs Figure 7), it can be observed that synchromodal dynamic solutions cope better with more severe disruptions, whereas shorter disruptions (profile Ψ2) do not require immediate deviations and proactiveness.

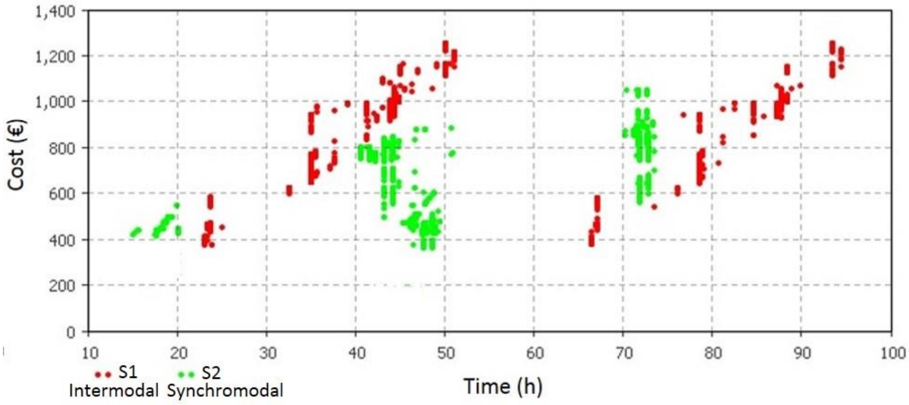

Figure 7: Comparison of order delivery performances after exposing simulation 1 and 2 (S1 and S2) to disruption profile Ψ3 for static intermodal (red) and dynamic synchromodal (green) solutions

A more representative overview of the results is shown in Figure 8 which demonstrates the strength of synchromodality once tested for all disruption lengths; the fluctuations in S2 (green) under profile Ψ3 are more stable than S1 (red) indicating rather unpredictable outcomes that can fluctuate widely. The proactive synchromodal nature of the S2 simulation reduces the delivery uncertainty by design; trucks avoid disrupted rail options whereas S1 is fully exposed to the rail disruptions. The small fluctuations in S2 (Figure 8, green) are cause by disruption profile 1 which delays trucks by 1 to 3 h. The design shows the benefits of a transparent user network that rests on information exchange and reactive behavior of assets which should form the efficient and connected Physical Internet flows.

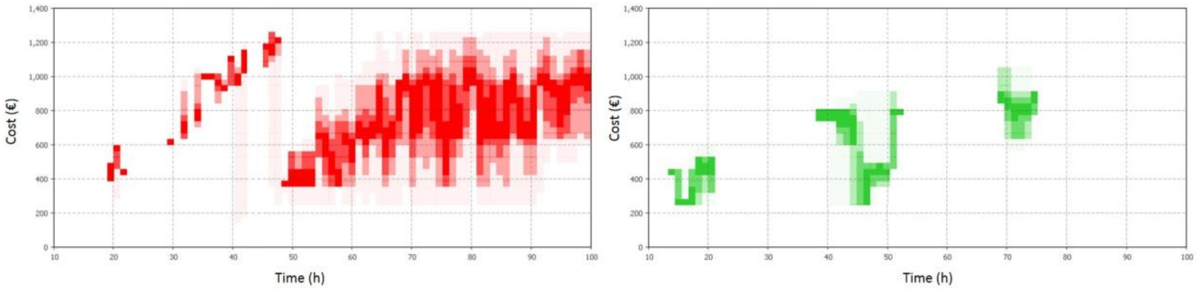

Figure 8: Monte Carlo experiments linked to Figure 7 with disruption profile Ψ3 for static intermodal (S1 red) and dynamic synchromodal (S2 green).

To this end, however, the simulations rely on network openness and benevolence of other carriers to flexibly change modes at any time in a virtual environment. New sensor technologies and techniques that can collect and integrate real-time information will be imperative to determine the disruption severity, its length and spatial occurrence in order to reduce uncertainties depicted by the probability distribution functions. The earlier mentioned network openness can be achieved through IoT technologies and geo-spatial coverage, by 5G network for instance, in order to reach out to assets by facilitating information exchange, remote-control and automation. But how can we connect the risk-free virtual environment and its functionalities to the physical system so that users can assess different what-if scenarios when needed? The next section sheds more light on this question but also on our second research question (*How can the digital twin concept/technology reduce uncertainties?).*

4.2 A Digital twin technology for synchromodality

The DTT should be able to interrogate assets and their context(s) that surround(s) them. The predictive elements will start from the historical and current asset states where the physical twins (PTs) will be queried with regard to their ongoing working conditions, current geolocations via latitude and longitude (x, y coordinates), their history states and performances. These parameters will form the basis of the DT, being the digital instance of the physical twin. The future projections will rely on the fidelity of physics that govern asset movements while taking into account information from external sources (AIS, weather forecasts, traffic jams, accidents, strikes, newly incoming orders, etc.). Figure 9 depicts how to transform PTs into DTs via a mirroring platform where real-physical assets can be converted into object instances. The Internet of Things (IoT) sphere contains many applications and technologies that can be incorporated in one coherent network. As the Physical Internet involves multiple companies with various geographical scales that require different reach, network coverage and different technologies need to be used for sensing objects. In this regard, connecting application silos as well as sensor/beacon technology and its attributes together will play an important role.

The “things” in the IoT notion need to have an environment that will be similar to the DTE and its coordinate system for accurate location intelligence and geo-fencing (as described in section 3.2). The DTE can then receive contextual information from the physical environment through real-time geo-servers that may integrate external sources of information at one reference point. Such servers allow for process integration via real-time data analytics once real-time data inputs are gathered.

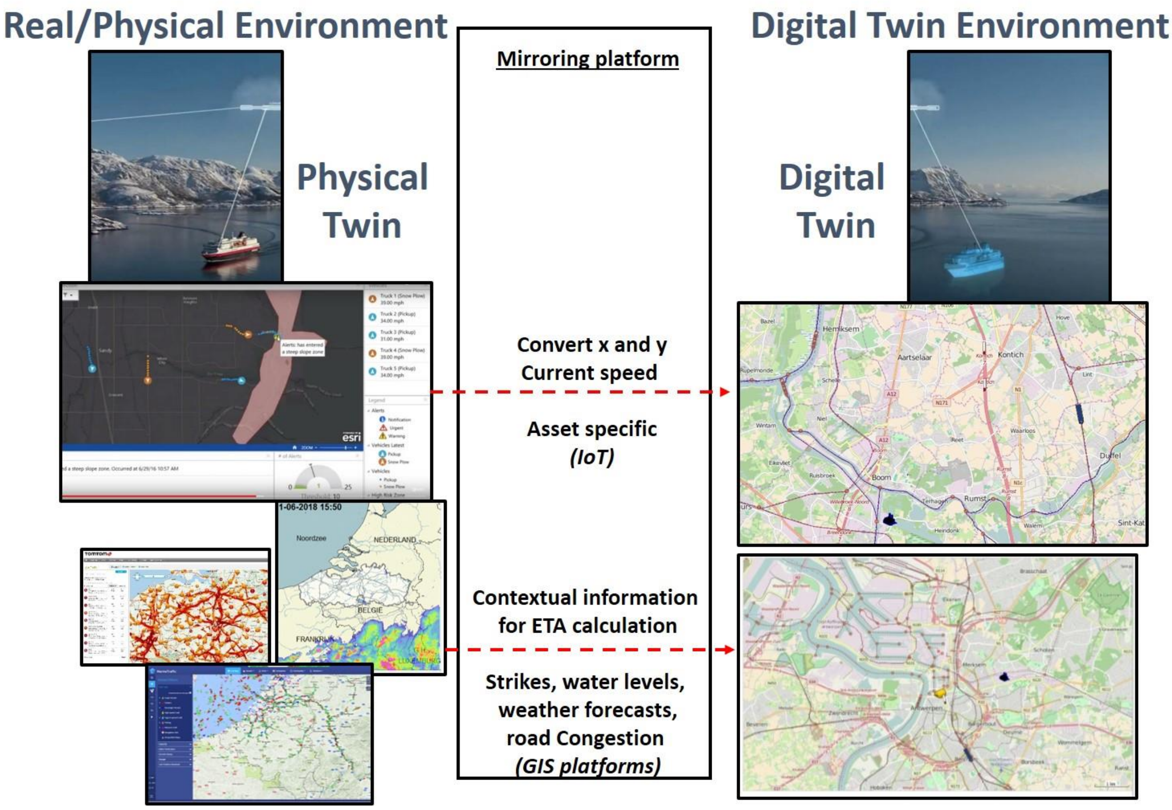

Figure 9: Demonstration of a mirroring platform. Left-hand side figures are borrowed from ESRI, waterinfor.be, marinetraffic.com and Mfame. Right-hand side is the virtual environment of our SYMBIT model.

As mentioned in the introduction, applications that monitor the physical environment (Figure 9, left-hand side) provide past and present positions of assets and trends. The real added value of the DTT is its ability speed-forward into the future to simulate and account for possible outcomes and uncertainties. Given the combination of data- and process-centric modelling, simulations will help by generating data and training models in situations that have never happened before; when reality kicks in alongside the simulation scenario trajectories, we will already have solutions as we will have tested those in the virtual world. By means of agent-based and discrete event modelling, it is possible to understand emergence of patterns and devise mitigation strategies in virtual geo-referenced space while taking into account external effects. Furthermore, decentralized algorithms can expose and tackle the “I didn’t see that coming” developments that may be realized only by having decentralized action taking based on individual spatial and temporal attributes of assets/agents with their objectives and biases.

In this regard, the DTT and its mirroring platform would query available assets, contextual information, and evaluate multiple scenarios in parallel as illustrated in Figure 10. Multiple digital instances/agents such as barges, trains, trucks, terminals and dc’s will feed data into the DTE where Monte Carlo simulations will take over and execute future possible states and patterns that may emerge once individual agents with their own biases and objectives start taking actions and affect each other. The Monte Carlo simulations will draw input values from probability distribution functions from historical and hypothetical disruption profiles, and impose delays, blockages and other events upon agents during model executions (as demonstrated in the previous section). These events trigger a transition from agents’ current ongoing process states to new “disrupted” composite states where agents will seek for alternatives from a decentralized perspective and their individual context (geo-location, distances, infrastructure etc.).

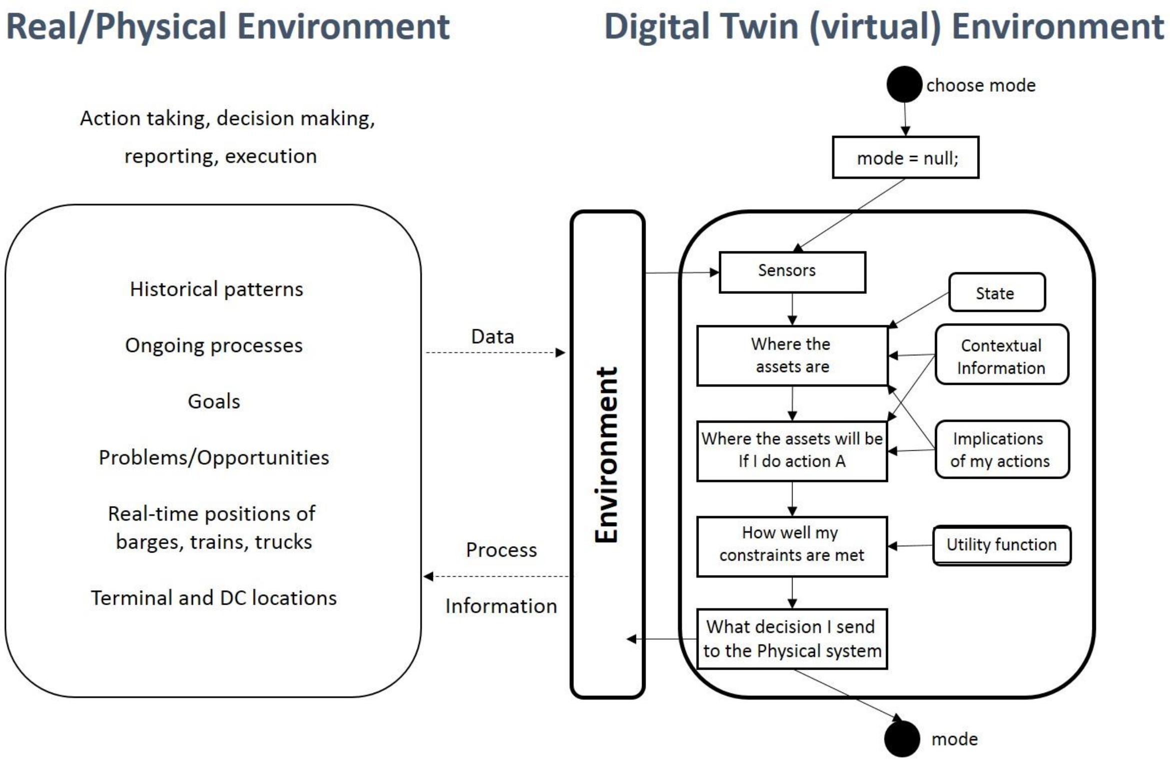

Figure 10: Conceptual illustration of the digital and physical Twin interaction. Right-hand side of the figure is adapted from Russell et al. (2003).

As indicated in Figure 10, the real physical system will provide data to the virtual space, and in return the virtual space will provide information flow and process specifications to the real system after evaluation several virtual sub-spaces (multiple virtual realities). Such a risk-free environment will allow for analysis and evaluation of triggering events (new orders, disruptions, delays…) which induce physical movements, and vice-versa, physical movements may trigger information flows once certain assets arrive at a specific location or enter a geo-fence. The moving (barges, trains, trucks, vans etc.) and stationary (terminals, DCs etc.) assets can be perceived as physical objects that can communicate their location to the DTE. As the Internet of Things deals with the *Intern*et as the network or virtual space, and *things* as physical objects (Atzori et al., 2010), the DTT can go beyond getting mere data out of sensors, and rather focus on the data processing mechanics, machine learning and business automation within the DTE. This is to say that the Digital Twin concept is not just a digital representation of a disconnected entity, but it shifts and updates alongside its physical counterpart and proceeds current physical reality to facilitate decision making by providing most probable outcomes. This can lead to optimization of routing and mode switching strategies with regard to which mode to use, where to switch, what terminals are located enroute, how far the handling points are and if the assets will make it before closing hours given the assets' current geo-locations.

5 Conclusion

The paper explored the digital twin concept and its potential role in synchromodal transport. From a methodological point of view, agent-based modeling has an ability to simulate information availability/exchange that is linked to consequent reactive agent behavior induced by it. This ability is tested in our SYMBIT model by exposing static and dynamic solutions to disruptions where individual agents reconfigure based on their positions in space and time. Knowing the state of the transport system and its evolution allows for more accurate and efficient policy rules to mitigate undesired effects of the system and its sub-parts. Synchromodal dynamic solutions are more relevant when dealing with longer-term disruptions as short-term disruption might not always yield better results if assets are managed too proactively; leading to unnecessary deviations that could increase delivery costs and lead-times. As far as the digital twin dimension of the paper is concerned, simulation-based solutions are useful for failure prediction, developing systems, new designs and optimization of various system processes. The digital twin concept presents an imperative step to fuse virtual models with physical environments and their processes. To further explore and deepen the understanding of digital twins for synchromodality, a new DISpATch (Digital twIn for SynchromodAl Transport) project has been set up by 4 knowledge centers and 13 companies in Flanders. DISpATch will focus on connecting the modelling logic embedded in virtual environments with the physical system processes, and vice versa. The project consortium will devote 4 years to this task by combining inventory managements algorithms, integrated network planning and freight transport uncertainty and predictability simulations.

Abbreviations

DT	Digital Twin
PT	Physical Twin
DTT	Digital Twin Technology
DTE	Digital Twin Environment
IoT	Internet of Things
GIS	Geographic Information System
Iww	Inland waterways
ABM	Agent-based modeling

References

- Alam, K. M., & El Saddik, A. (2017). C2ps: A digital twin architecture reference model for the cloud-based cyber-physical systems. *IEEE Access, 5*, 2050-2062.
- Ambra, T., Caris, A., & Macharis, C. (2019a). Should I Stay or Should I Go? Assessing Intermodal and Synchromodal Resilience from a Decentralized Perspective. *Sustainability, 11*(6), 1765.
- Ambra, T., Caris, A., & Macharis, C. (2019b). Towards freight transport system unification: reviewing and combining the advancements in the physical internet and synchromodal transport research. *International Journal of Production Research, 57*(6), 1606-1623.
- Atzori, L., Iera, A., & Morabito, G. (2010). The internet of things: A survey. *Computer networks, 54*(15), 2787-2805.
- Bak, P. (1996). How nature works: the science of self-organized criticality. *Nature, 383*(6603), 772-773.
- Batty, M. (2018). Digital twins. *Environment and Planning B: Urban Analytics and City Science, 45*(5), 817-820. doi:10.1177/2399808318796416
- Boschert, S., & Rosen, R. (2016). Digital twin—the simulation aspect *Mechatronic Futures* (pp. 59-74): Springer.
- Brenner, B., & Hummel, V. (2017). Digital twin as enabler for an innovative digital shopfloor management system in the ESB Logistics Learning Factory at Reutlingen-University. *Procedia Manufacturing, 9*, 198-205.

- Erikstad, S. (2017). *Merging Physics, Big Data Analytics and Simulation for the Next-Generation Digital Twins*. Paper presented at the 11th Symposium on High-Performance Marine Vehicles, Zevenwacht, South Africa.
- Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems *Transdisciplinary perspectives on complex systems* (pp. 85-113): Springer.
- Knapp, G. L., Mukherjee, T., Zuback, J. S., Wei, H. L., Palmer, T. A., De, A., & DebRoy, T. (2017). Building blocks for a digital twin of additive manufacturing. *Acta Materialia, 135*, 390-399.
- Pettey, C. (2017). Prepare for the Impact of Digital Twins. *Gartner: Stamford, CT, USA*.
- Russell, S. J., Norvig, P., Canny, J. F., Malik, J. M., & Edwards, D. D. (2003). *Artificial intelligence: a modern approach* (Vol. 2): Prentice hall Upper Saddle River.
- Schleich, B., Anwer, N., Mathieu, L., & Wartzack, S. (2017). Shaping the digital twin for design and production engineering. *CIRP Annals, 66*(1), 141-144.
- Shafto, M., Conroy, M., Doyle, R., Glaessgen, E., Kemp, C., LeMoigne, J., & Wang, L. (2012). Modeling, simulation, information technology & processing roadmap. *National Aeronautics and Space Administration*.
- Söderberg, R., Wärmefjord, K., Carlson, J. S., & Lindkvist, L. (2017). Toward a Digital Twin for real-time geometry assurance in individualized production. *CIRP Annals, 66*(1), 137-140.
- Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., & Sui, F. (2018). Digital twin-driven product design, manufacturing and service with big data. *The International Journal of Advanced Manufacturing Technology, 94*(9-12), 3563-3576.
- Uhlemann, T. H.-J., Schock, C., Lehmann, C., Freiberger, S., & Steinhilper, R. (2017). The digital twin: Demonstrating the potential of real time data acquisition in production systems. *Procedia Manufacturing, 9*, 113-120.
- Zheng, Y., Yang, S., & Cheng, H. (2019). An application framework of Digital Twin and its case study. *Journal of Ambient Intelligence and Humanized Computing, 10*(3), 1141-1153.