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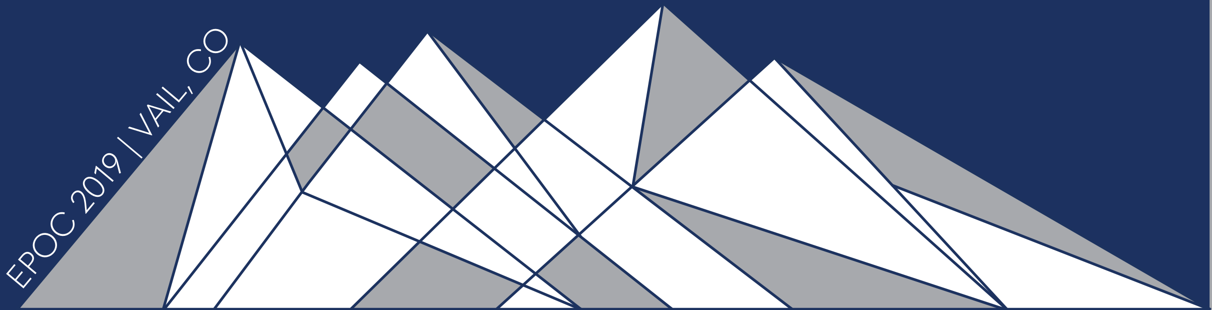

DETECTING JOINT INVESTMENT OPPORTUNITIES AMONG INTERDEPENDENT INFRASTRUCTURE SYSTEMS

Sahand Asgarpour[1], **Andreas Hartmann**[2]

ABSTRACT

Infrastructure systems (e.g. road, rail, energy, water) currently require vast amount of investments to be able to respond to short- and long-term social, technological and environmental developments such as an increasing mobility demand, and the transition towards alternative energy solutions. Currently most of the investments are planned through a silo-based approach ignoring interdependencies among infrastructure systems and by doing so missing scale and innovation opportunities. Although scholars have paid much attention to the risk of infrastructure interdependencies as response to exogenous threats like climate change and terrorism, studies on the opportunities for joint investments emerging from infrastructure interdependencies are scarce. This paper proposes a framework and an agent-based model at its core to assist decision-makers at infrastructure agencies to (i) introduce sector-specific investment portfolios, and (ii) identify investment opportunities upon which they can form cross-sectoral resource alignments and integration. The framework allows infrastructure agencies to reveal infrastructure interdependencies by simulating the propagated state changes induced through sector-specific investments.

KEYWORDS

Agent-based modelling, Infrastructure interdependencies, Infrastructure investments

INTRODUCTION

Infrastructure systems are vital to the economic prosperity and social well-being of countries. Infrastructures consist of numerous heterogeneous sub-systems with non-linear interactions. They do not function in isolation and are often interdependent with bidirectional relationships “through which the state of each infrastructure influences or is correlated to the state of the other. More generally, two infrastructures are interdependent when each is dependent on the other” (Rinaldi et al. 2001, p.14). For example, trains transport fuel for energy generation (coal, oil), while railways need electricity to power trains through overhead catenaries. Advances in ICT and

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automation are further increasing the informational and functional interdependencies of infrastructures.

Decision makers at infrastructure agencies (institutional actors within infrastructure systems) introduce adaptations to the systems through investment pathways (in technical or organizational layers). Adaptations that require vast amounts of investments to ensure meeting the current requirements of reliable and constant delivery of infrastructure services next to enabling an adequate response to future challenges.

Investments exert changes in infrastructure components that create emerging interdependencies with new or existing components. Such emergent patterns of state changes at lower levels of infrastructure can change the interactions at higher-levels with different technical and organizational implications. For example, providing and managing the infrastructures that deliver heat for buildings from the waste heat of chemical and petrochemical processes in a port, creates the possibility for the port and energy providers to start collaboration and forming new alliances. Thus, approaching investments across sectors can stimulate infrastructure agencies to collaborate in planning, realizing, and managing investment outcomes. Such an alignment in activities in the phase of strategy forming can lead to detecting joint investments.

Infrastructure interdependencies became under the focus of governments and researchers in order to protect critical infrastructure systems from disruptive events and respond adequately to recover the systems while ensuring critical functionality. This resulted in identifying different types of interdependencies (Dudenhoeffer et al. 2006; E. E. Lee et al. 2007; Rinaldi et al. 2001; Zhang and Peeta 2011; Zimmerman 2001; Zimmerman 2004), and modeling and simulating the possible effects on and from interconnected infrastructure to increase the resilience of critical infrastructure (e.g. Zimmerman 2004, Ouyang, Hong et al. 2009, Ge, Xing et al. 2010, Eusgeld, Nan et al. 2011, Zhang and Peeta 2011, Ouyang 2014, Zhang and Peeta 2014, Wu, Tang et al. 2016, Bloomfield, Popov et al. 2017, Saidi, Kattan et al. 2018). Limited work has been done on the opportunities for joint investments arising from infrastructure interdependencies (Hall, Henriques et al. 2012, Young and Hall 2015, Moloney, Fitzgibbon et al. 2018). Existing studies focus on constructing and assessing different scenarios for infrastructure provision strategies based on certain performance metrics (Tran, Hall et al. 2014, Hall, Tran et al. 2016). This top-down approach for strategic planning of infrastructures and tracing cross-sectoral supply-demand dynamics is less applicable for identifying investment opportunities of interdependent infrastructure. This is because infrastructure investments are mainly planned and realized through a silo-based approach (Busscher et al. 2015; Glorioso and Servida 2012; Moloney et al. 2018; Otto et al. 2016; Roelich et al. 2015; Young and Hall 2015). Central to this approach is the incomplete insight and undocumented knowledge of infrastructure interdependencies. Moreover, there is an insufficient information exchange among infrastructure agencies regarding the sector-specific investment plans, which can shape possible collaborations among agencies. Opportunities arising from the interdependencies among infrastructure networks are hence missed. This requires a bottom-up modelling approach, which can explore possible emerging state changes in interconnected infrastructures and possible future evolution pathways in a more flexible manner. System components are able to take future development pathways - which suggest different investment pathways- based on incorporated and quantified interdependencies. In that regard, physical connection and co-location of system components intensify the interaction among infrastructure systems, as due to vicinity, the effects of changes in system components of one infrastructure can be felt closely in the other. Thus, it is important to incorporate spatial analysis to reveal the physical and spatial overlaps to inform decision-makers from the possibilities of alignments in planning and executing investment activities.

There are various modeling techniques proposed in the literature including (Ouyang 2014; Saidi et al. 2018): *Agent-based modeling*, *Economic theory approaches*, *Empirical approaches*, *Network-based modeling*, and *System Dynamics*. Among these different modeling techniques, agent-based modeling is a suitable method to model complex systems and simulate the bottom-up emergent behavior of actors in investment decision-making processes (Dijkema et al. 2012). It links the micro behavior of actors to the state that will be emerged at the macro-level, which are dynamically changing and evolving over time (Adelt et al. 2014).

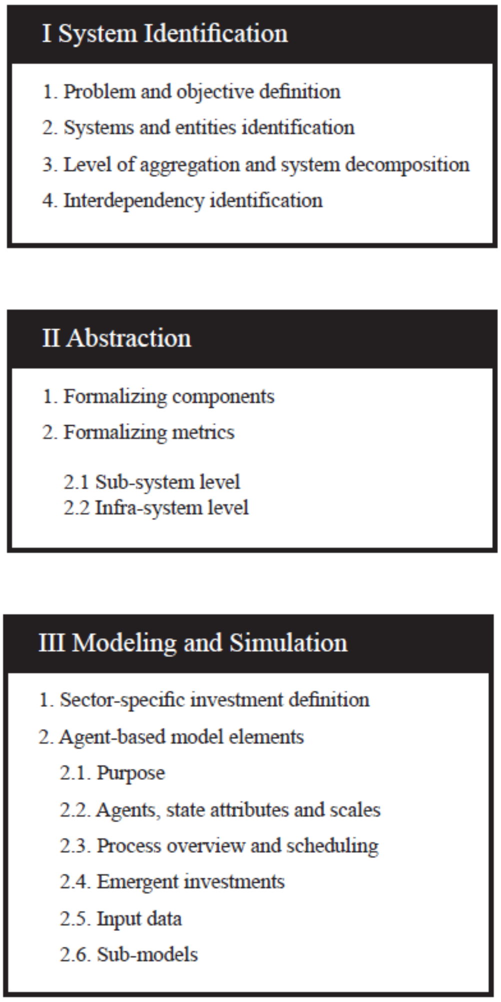
For the above reasons, the paper proposes a modeling framework and an agent-based model at its core that reveals infrastructure interdependencies, and simulates the propagated state changes induced by sector-specific investment. The framework is able to assist decision-makers in (i) mid-term and long-term infrastructure planning, (ii) exploring the emergent state changes of infrastructure as a result of sector-specific investments, and (iii) identifying investments upon which they can form cross-sectoral resource alignment and integration. This modeling framework enables us to perform spatial analysis to detect spatial overlaps of system components involved in investments, to inform decision-makers about possible alignments. These possible alignments can create opportunities for cross-sectoral collaborations.

With the framework, we shift the focus of modeling and simulating infrastructure interdependencies from the resilience perspective to the opportunities as the other side of the interdependency coin. We advance the understanding of infrastructure interdependencies by proposing a bottom-up modeling approach for sector specific investments and their cross-sectoral interactions forming future development pathways. Next to that, this framework takes into account the geographical and physical interdependencies next to the functional interdependencies, which adds to the existing studies by performing spatial analysis.

By providing a systematic approach toward integrated infrastructure provision, the paper relates to the system integration challenge. It shows how infrastructure agencies can be supported in understanding larger societal, environmental and technological changes as opportunities rather than risks. In the next section, we explain the developed framework and end the paper with conclusion and future works.

MODELING FRAMEWORK

The complex systems of interdependent infrastructures have traits such as operational and managerial independence, heterogeneity, and evolutionary behavior (DeLaurentis 2008), which can be characterized as System-of-Systems (SOS). Based on the SOS perspective we introduce three main stages for the modeling framework: (i) system identification, (ii) abstraction, and (iii) modeling and simulation.



I System Identification

1. Problem and objective definition
2. Systems and entities identification
3. Level of aggregation and system decomposition
4. Interdependency identification

II Abstraction

1. Formalizing components
2. Formalizing metrics
    2.1 Sub-system level
    2.2 Infra-system level

III Modeling and Simulation

1. Sector-specific investment definition
2. Agent-based model elements
    2.1. Purpose
    2.2. Agents, state attributes and scales
    2.3. Process overview and scheduling
    2.4. Emergent investments
    2.5. Input data
    2.6. Sub-models

Figure 1: Stages of the modeling framework

SYSTEM IDENTIFICATION

This stage includes the identification of actors, systems, components, and existing interdependencies. We based this stage on the works of Bloomfield et al. (2017), DeLaurentis (2008), Eusgeld et al. (2009); Eusgeld et al. (2011), and Van Dam et al. (2012), and fit them to the purpose of this modeling framework. It assists in detecting and decomposing infrastructure systems, which requires close collaboration of stakeholders and an iterative process to gain sufficient system understanding and provide a complete system decomposition.

1. PROBLEM AND OBJECTIVE DEFINITION:

A well-defined problem ensures considering the required systems' environment (e.g. technical, organization) components, actors, interactions, with sufficient level of aggregations. Better context is given to the problem by defining temporal horizon to consider sector-specific investments and their effects, spatial scale, types of resource alignment and integration among infrastructures, and defining certain concepts. For the purpose of the framework, it is necessary to reach the same understanding among different stakeholders about the problem and further define the insights that are expected to be gained:

i. We propose to set the time horizon to 2030 for introducing sector-specific investments, as we aim to include investments in the model that are concretized as far as possible. However, the effect of the investment is more long-term, consequently we run the model until 2070.

ii. The framework suggests one of the following spatial scales: municipal, provincial, national, or international.

iii. It is crucial to make sure that stakeholders have relatively similar understanding of concepts. In this framework we consider *investment* as the resource allocations toward an infrastructure project based on an identified need for some product, facility, or asset (Lewis 2016). We look from the construction to the demolition phase of asset life cycle. Hence, projects incorporate different spans of life cycle based on type of contract. Including and assessing the influence of types of contract on the cross-sectoral collaboration of infrastructure agencies are out of the scope of this framework. Moreover, we consider joint investment opportunities as the investment opportunities upon which they can form cross-sectoral resource alignments and integration. Concepts to be clarified are not limited to the mentioned ones above. In this framework, when a concept is introduced, we aimed to present its definition and the purpose of its implementation.

2. SYSTEMS AND ENTITIES IDENTIFICATION:

Infrastructure systems should be defined within the scope and interest of stakeholders. Thus, the framework provides in total three different generic *sub-systems* for each infrastructure system (infrasystem), which receive and exert influences upon one another. On the supply side, we distinguish between the two following sub-systems:

i. *Operational:* Contains to the physical components of infrastructures required for the functionality of the system.

ii. *Organizational:* Contains the social entities and the regulations upon which they perform tasks infrastructure agencies. These tasks encompass mainly a range of designing, constructing, operating and maintaining of the operational sub-systems.

On the demand side, we define:

iii. *Consumer*: Contains the end-users of the infrasystems' products and services, who interact with the infrasystems via physical entities. Infrasystems can also be a costumer of another infrasystem. The consumer sub-system thus contains both physical and social entities that can be separated into distinguished sub-systems (for example when considering an infrasystem as a consumer).

In the context of infrasystem investments, numerous entities interacting among and within multiple infrasystems and their sub-systems. Hence, it is important to define the scope further by including the relevant layers of environment and entities. This is depending among others on the extent to which there is access to relevant data or computational power.

3. LEVEL OF AGGREGATION AND SYSTEM DECOMPOSITION:

After defining the infrasystems, related environments, and entities, we need to know the finest scale of the entities. Decision about the level of aggregation should be aligned with the spatial scale of interest (step 1). Moreover, it should be noted that the finer the level of aggregation, the higher the computational power is required for modeling and simulation, and running the model will be more time consuming. Knowing the entities' level of detail will enables us to determine the constituents of the infrasystems; in the other words, we can decompose the infrasystems.

Defining the level of aggregation for technical entities is context dependent including factors such as spatial scale and involved environments. We can generalize this (from coarse to fine) into the following: *(i) Sector-level*: Collection of assets that represent the main functions of the different environment layers of infrasystems, such as road sector with the main function of allowing safe, reliable movements of goods and people. *(ii) Asset-level*: we use the definition of Thacker et al. for assets, which are "distinct physical components of the infrastructure that perform a specific function and that are critical for its operation" (Thacker et al. 2017), for example bridges. (iii) *Component-level*: components are the biggest constituents of an asset, with specific function, for example girders of a bridge.

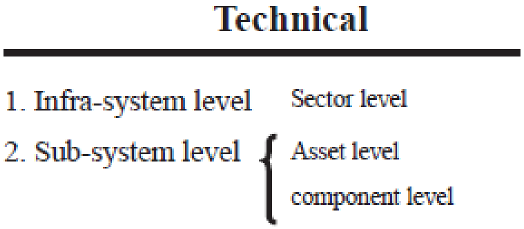


Figure 2: System entities and level of aggregation

4. INTERDEPENDENCY IDENTIFICATION:

The last step of system identification covers the identification of interdependencies among infrasystems. We define the following types of interdependency, which can be defined in close engagements of the stakeholders, who have enough knowledge of the environments within which they play a role.

i. Budgetary: refers to the involvement of entities in some level of public financing, especially under a centrally controlled economy or during disaster recovery (Dudenhoeffer et al. 2006).
ii. Distributional: When one entity depends on the other infrastructure to distribute a product or a service.
iii. Geographical: When entities are in close spatial proximity (Dudenhoeffer et al. 2006; Pederson et al. 2006; Rinaldi et al. 2001).
iv. Informational: An entity has an informational dependency on another if its state depends on information transmitted (data) (Dudenhoeffer et al. 2006; Pederson et al. 2006; Rinaldi et al. 2001).

v. Input: When functionality of one entity relies on a product or service as an input produced by another entity (E. E. Lee et al. 2007).
vi. Physical: When entities are coupled through shared physical parts (Dudenhoeffer et al. 2006; Pederson et al. 2006; Zhang and Peeta 2011).

This framework initially aims to include operational sub-system of infrasystems from supply side and consumers from demand side. However, we have laid the grounds to extend the framework to include organization sub-systems and interdependencies in future works.

ABSTRACTION

Having identified the system boundaries, components and interaction, we now move to the second step of the framework to formalize the detected entities and concepts. We propose to do so in three steps: *(i) component formalization, (ii) metrics formalization.*

1. FORMALIZING COMPONENTS

In this step, we formalize concepts defined in the system identification stage. Infrastructures are interdependent networks with flowing resources, that provide services at certain demanded level of the flow (E. E. Lee et al. 2007). We defined the level of aggregations in the system identification step into two infrasystem (sector level) and sub-system level (Figure 1). Let S be a set of infrasystems under studies, which is at the sector-level of aggregation. If it is decided to go deeper in the level of aggregation of the physical entities, each S_k is a set of graphs (N_k, E_k). Where N_k is set of nodes representing the asset-level or component-level entities of infrasystem k. Infrasystems are distinguished by their main activities, services and resources they deliver. Moreover, the ownership of the constituent components are also a criterion that define the boundaries of the infrasystem entities. E_k is a set of intra-system, directed edges of sector k. N_k are sub-systems that generate (source), consume (sink), or distribute (intermediate) certain services within the infrasystem k. For instance, railway stations consume electricity provided by power generation plants, hence it is a sink node for electricity. While it is both source and sink node for freight and passengers it is a point of both entry and exit (Pant et al. 2016). We assign sets of Θ, Φ, and Ψ as sets that contain respectively source, sink, and intermediate nodes. Cases may arise that a sub-system (node) changes its type. One of the main examples is major storage facilities or electric batteries, that store a certain resource for a certain period of time. In that case, they are considered as sink nodes. When it is needed, they can act as source nodes to provide resources.

A set of *intra-system* directed edges of E_k represents physical and non-physical connections among the nodes within the infrasystem k, which are the means to flow the resources within the set R. R is a set that contains all types of resources delivered to, generated, and distributed by all infrasystems, and ordered in alphabetic order. These are resources such as electricity, containers, or human entities such as passengers. We define the set of *Intra-system Edges* E_k^j, all edges that connect two nodes in the same infrasystem k that flow resource r_j. There are physical and non-physical connections among components of two infrasystems of k and l, which form a set of inter-system, directed edge E_{kl}. Similarly, the set of *Inter-system Edges* E_{kl}^{j}, is defined to contain all edges that connect infrasystems *k* and *l* by flowing the resource r_j.

In general, we define a directed edge between two infrasystems of a and b as $e_{ax,by}^{j}$ by a three tuple of (N_{ax}, N_{by}, r_j), where N_{ax} and N_{by} is x^{th} *and* $y^{\ th}$ nodes of node-sets of infrasystems a and b (N_a and N_b). r_j is the j^{th} resource of the set R_k and flows through the edge $e_{ax,by}^{j}$, between the nodes N_{ax} and N_{by}. N_{ax} is a source and N_{by} is a sink node. nr_{ki} states the number of resource type delivered to, generated, or distributed by node N_{ki}. The set *of ingoing edges* of E_{ki}^{j+} of N_{ki} contains all the edges to which the edges are directed. Contrarily, the set of *outgoing edges* of E_{ki}^{j-} of N_{ki} contains all the edges from which the edges are directed.

Resources are the first model instances by which, any state change may trigger consequent state changes in the interconnected node. This trigger is introduced through the interdependencies that are detected in the fourth step of the system identification stage. As mentioned before, the scope of this framework includes only geographical and functional (inter)dependencies, which are distributional, informational, input, and physical interdependencies. Geographical interdependencies are spatial interactions among specific components of the systems (nodes and edges), that can be formalized by through coupling GIS with agent based model environment (Figure 3).

This can be done by defining spatial buffers representing the spatial boundaries of the infrasystem components. Overlaps hence are considered as geographical interdependency (two-way dependency). Physical interdependency (two-way dependency) is captured by physical edges among nodes. At this step, we formalize distributional, informational, and input dependencies as *intake flow*, which delivers certain resources (e.g. freight, electricity or information) *distribute or consumed* during a process to generate certain service, which can contain both physical and non-physical edges (e.g. cables and wireless infrastructures). Through intake flow, different types of resources are received at nodes and will be delivered through the edges to the other components of the network. Resource types are distinguished in this modeling framework, as well as different types of nodes that are grouped in three sets of Θ, Φ, and Ψ. Thus, intake flow can represent distributional, informational, and input interdependencies identified in the system identification stage.

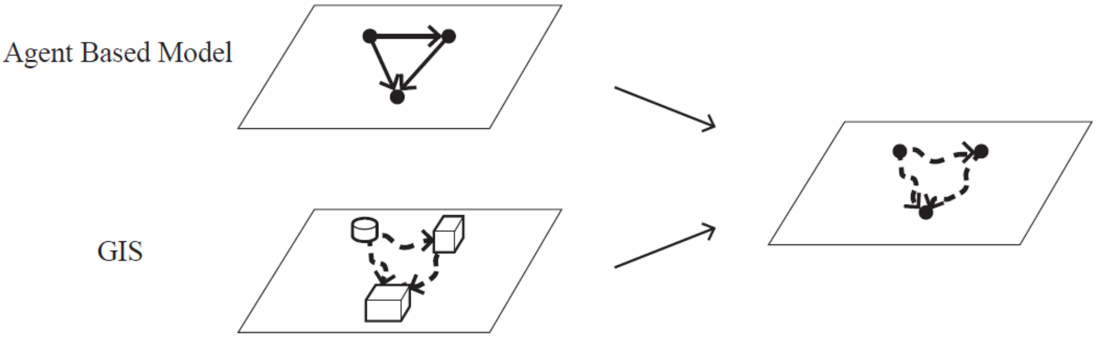


Figure 3: Coupling ABM and GIS environments

2. FORMALIZING METRICS

Having formalized the relevant components of the systems, we formalize necessary metrics that enables modeling and simulation of the infrasystems' normal state of operation. On the higher level, we define two main metrics of *resource delivery* (constrained by entities *capacity)* and *resource demand*. We propose to formalize the metrics in two levels of *sub-system* and *infrasystem*.

Sub-system level

Nodes

A sub-system components (as a node) in general demands and supplies certain resources that are constrained to the capacity factors of the components. We define *resource demand* RD_{ki}^{j} as the sum of the resource r_j demanded by the node N_{ki} at time T= t to provide specific functionalities, that are delivered to the node by the ingoing set of edges E_{ki}^{j+}. RD_{ki}^{j} is a function of time T and a set of sector-specific metrics A_k^{RD}, such as freight transportation costs per modality.

On the supply side, we define resource supply RS_{ki}^{j} as the sum of the resource r_j delivered in the node N_{ki} at time T= t, that are delivered to the node by the ingoing set of edges E_{ki}^{j-}. Same as resource demand, RS_{ki}^{j} is a function of time T and a set of sector-specific metrics A_k^{RS}. For instance, the amount of containers delivered in a specific year (TEU, Twenty-feet Equivalent Unit), is a function of the time and sector-specific metrics such as capacity of port intermodal terminals.

Resource demand and supply of the node N_{ki} at time T= t are constrained the following capacity functions:

$$CD_{ki}^{minj}(t) \leq RD_{ki}^{j}(t) \leq \; CD_{ki}^{maxj}(t) \qquad \text{Condition 1}$$

$$RS_{ki}^{j}(t) \leq CG_{ki}^{j}(t) \qquad \text{Condition 2}$$

Where $\mathrm{CD}_{\mathrm{ki}}^{\mathrm{minj}}$ is the minimum capacity that is demanded and required for the functionality of the node. CD_{ki}^{maxj} is the maximum capacity that can be demanded by the node. This refers to the maximum amount of resource r_j that the node can accommodate. CG_{ki}^{j} is the *capacity of generation* of resource r_j by the node. Capacity functions are in general functions of time T and a set of sector-specific metrics A_k^{C}.

Edges

Edges are responsible to flow resources among nodes within different infrasystems. Here we define *Edge Flow* $EF_{ax,by}^{j}$ for edge $e_{ax,by}^{j}$ at time t, which delivers *fraction* of the outgoing service of resource r_j, from node N_{ax} to node N_{by}:

$$EF_{ax,by}^{j}(t) = \; RS_{ax}^{j}(t) \times \beta_{ax,by}^{j}(t) \qquad \text{Equation 1}$$

Where $\beta^{j}_{ax,by}$ is the *Edge Weight* that represents the fraction of the resource r_j supplied, from node N_{ax}, with the condition that sum of all Edge Weights of outgoing edges of node N_{ax} is 1, $\sum_{\forall e\subseteq E^{j-}_{ax}} \beta^{j}_{ax,by} = 1$.

Edge Flow is constraint to the Capacity of Flow $CF^{j}_{ax,by}$, which is a function of time T and sector-specific metrics A^{EF}_{k}:

$$EF^{j}_{ax,by}(t) \leq CF^{j}_{ax,by}(t)$$ Condition 3

Having defined edge flow, we now formalize the earlier defined RS^{j}_{ki} and RD^{j}_{ki}:

$$RS^{j}_{ki}(t) = \sum\nolimits_{\forall e\subseteq E^{j-}_{ki}} EF^{j}_{ki,by}(t)$$ Equation 2

$$RD^{j}_{ki}(t) = \sum\nolimits_{\forall e\subseteq E^{j+}_{ki}} EF^{j}_{ax,ki}(t)$$ Equation 3

In the other words, this relationship sates that the resource demanded should be met in the normal state of functioning.

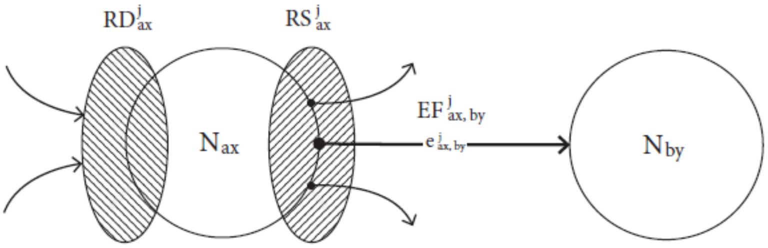


Figure 4: Node and edge main attributes

Metrics of Change

Resource supply change for node N_{ki} is defined as the ratio of the resource supply of time $t_2$to t_1. This enables us to track variations in resource supply functions due to exerted changes, for example by investing in a sub-system of an infrasystem.

$$RSC^{j}_{ki}(t_2, t_1) = \frac{RS^{j}_{ki}(t_2)}{RS^{j}_{ki}(t_1)}$$ Equation 4

Similarly, we define Resource demand change to represent resource demand changes in time t. This is the ratio of the resource demand of time $t_2$to t_1.

$$RDC^{j}_{ki}(t_2, t_1) = \frac{RD^{j}_{ki}(t_2)}{RD^{j}_{ki}(t_1)}$$ Equation 5

For all types of capacity functions mentioned for nodes and edges, we define capacity changes, that enables us to model changes introduced by investments in the sub-systems of infrasystems. This is the ratio of the capacity functions of time $t_2$to t_1 for node N_{ki}:

$$CDC_{ki}^{minj}(t_2,t_1) = \frac{CD_{ki}^{minj}(t_2)}{CD_{ki}^{minj}(t_1)}$$ Equation 6

$$CDC_{ki}^{maxj}(t_2,t_1) = \frac{CD_{ki}^{maxj}(t_2)}{CD_{ki}^{maxj}(t_1)}$$ Equation 7

$$CGvar_{ki}^{j}(t_2,t_1) = \frac{CG_{ki}^{j}(t_2)}{CG_{ki}^{j}(t_1)}$$ Equation 8

$$CFvar_{ki}^{j}(t_2,t_1) = \frac{CF_{ki}^{j}(t_2)}{CF_{ki}^{j}(t_1)}$$ Equation 9

One of the metrics that depicts more clear understanding of sub-systems' performance in a specific period, is to measure the extent of which the capacity functions mentioned above are utilized by corresponding function of resource supply, demand, and flow. We use the metric ***capacity margin*** introduced by (Tran et al. 2016):

$$CM_k^j = \frac{Capacity\ functions - Utilization\ functions}{Capacity\ functions} \times 100$$ Equation 10

Where $\mathrm{CM}_\mathrm{k}^\mathrm{j}$ presents capacity margin of entity (node or edge) infrasystem *k* for resource r_j, and *Utilization* functions are resource supplied, resource demanded, and edge flow, which correspond respectively to their *capacity functions*: capacity of generation, maximum aggregated capacity of demand, and aggregated capacity of flow.

Another metric to demonstrate changes in sub-systems are *unavailability* and *life-cycle performance indicator (LPI)* of infrasystem components (nodes and edges). Unavailability represents the amount of days that the component is not able to function in a year, and performance of the aging sub-systems. We defined this metric to take into account the impact of major investments, which temporarily disable the functionality of the components to perform maintenance activities. Moreover, LPI indicates the effect of aging on the performance of the sub-system components (assets). LPI is influenced by "time-dependent deterioration effects of aging and damage processes of structural materials and components" (Biondini and Frangopol 2016). It is considered in this modeling framework to capture the necessity of performing maintenance activities at an expected point of time on sub-system components. After performing the maintenance activities, LPI will be updated. In this research, we define LPI^{max} as the maximum sub-system theoretical age at which performing the maintenance activities become necessary. For a collection of assets, the maximum theoretical age of the involved assets is considered.

Dependency formalization

Infrasystems convey resources to one another through inter-system edges. These resources are transformed in the sink nodes to the resource that is considered as (one of) the main service of the infrasystem, hosting the sink node. For instance, electricity infrasystem delivers electricity to railway traction substation, which provide train power. Thus, the electricity as a delivered resource to railway infrasystem is converted to train kilometers, which represents the resources provided by railway as a service (commuting passengers and freights). The dependency between railway and electricity infrasystems falls within the intake flow.

There are nodes that through a process, transform a type of resource delivered to them into other type of resource, as their supplied resource. For example, gas power stations transform a cubic meter gas to a certain kWh electricity. In order to formalize resources transformation, shaped by intake flow, we define the following. The amount of resource supplied r_q by node N_{ki}, from the amount of resource r_p delivered at the node (RD_{ki}^{p}) is calculated by *Resource Transform* function at node N_{ki}:

$RT_{ki}^{pq}(t) = TF^{pq}(RD_{ki}^{p}(t))$ Equation 11

Where TF^{pq} is the function that transforms the amount of resource r_p to r_q, and there are models required to obtain this transformation. It is assumed that this function is equal for all nodes that convert r_p to r_q. For example, the amount of electricity needed for powering railways, and running certain amount of trains. Depending on the scope of the model, in terms of interdependencies to be captured among infrasystems, these resource transform functions should be established.

In order to ensure the functionality of a node (demand met), we define the following. Assume a set of primary resource $Rp_k \subseteq R_k$that contains all resources that are transformed at N_{ki} to the resource r_q, supplied by node N_{by}. Then:

$RS_{ki}^{q}(t) \leq RD_{ki}^{q}(t) + \sum_{\forall p \in Rp^q} RT_{ki}^{pq}(t)$ Condition 4

In the condition mentioned above, since r_q can be consumed in the node N_{ki}, the condition is not presented in the form of equation. Another condition is that the $RD_{ki}^{p}(t)$ should be constrained by capacity functions of delivering edges and generating nodes. Consider V_{ki} as the set of source nodes of E_{ki}^{j+}:

$\mathrm{RD}_{\mathrm{ki}}^{\mathrm{p}}(\mathrm{t}) \leq \sum_{\forall \mathrm{N}_{\mathrm{ax}} \in \mathrm{V}_{\mathrm{ki}}} \mathrm{CG}_{\mathrm{ax}}^{\mathrm{p}}(\mathrm{t})$ Condition 5

$\mathrm{RD}_{\mathrm{ki}}^{\mathrm{p}}(\mathrm{t}) \leq \sum_{\forall \mathrm{e} \subseteq \mathrm{E}_{\mathrm{ki}}^{\mathrm{j+}}} \mathrm{CF}_{\mathrm{ax,ki}}^{\mathrm{p}}(\mathrm{t})$ Condition 6

If $Rp^q = \emptyset$, then $\sum_{\forall p \in Rp^q} RT_{by}^{pq}(t) = 0$, which it is still valid for the nodes when there is no transformation function involved. If the transformation function is *required* for the functionality of the node (electricity for powering railways), or in the other word, RD_{ki}^{minp} is required for its functionality, then:

$RD_{ki}^{p}(t) < RD_{ki}^{minp}(t) \rightarrow RS_{ki}^{q}(t) = 0$ Condition 7

Infrasystem level

In this section, we formalize the relevant infrasystem metrics, which represent aggregated performance, demand, and sector-specific metrics of the constituent sub-systems. Starting with the metrics from the ***demand side***, we define *Aggregated Resource Consumed* ARC_k^j for resource r_j, which set of sink nodes of infrasystem *k* at a specific time consume:

$ARC_k^j(t) = \sum_{\forall N_{ki} \in \Phi_k} (RD_{ki}^{j}(t) - RS_{ki}^{j}(t))$ Equation 12

We define *aggregated resource supplied* for the ***supply side***, for resource r_j, which set of source nodes of infrasystem *k* at time T=*t* generated:

$$ARS_k^j(t) = \sum_{\forall N_{ki} \in \Theta_k} (RS_{ki}^j(t) - RD_{ki}^j(t)) \qquad \text{Equation 13}$$

Aggregated edge flow is defined to represent the total resource r_j that is distributed in infrasystem *k* at a specific time:

$$AEF_k^j(t) = \sum_{\forall e \subset E_k} EF_{ax,by}^j(t) \qquad \text{Equation 14}$$

For the ***capacity functions,*** we define the following metrics:

1. *Aggregated capacity of flow* is the sum of the capacity of flow of all edges within one infrasystem, for resource $r_{j,}$

$$ACF_k^j(t) = \sum_{\forall e \subset E_k} CF_{ax,by}^j(t) \qquad \text{Equation 15}$$

2. *Aggregated capacity of generation* is the sum of the capacity of generation of all nodes in infrasystem *k*, generating resource r_j*:*

$$ACG_k^j(t) = \sum_{\forall N_{ki} \in N_k} CG_{ki}^j(t) \qquad \text{Equation 16}$$

3. *Maximum aggregated capacity of demand* is the sum of the maximum capacity that can be demanded by all nodes of infrasystem *k*, for resource r_j*:*

$$ACD_k^{maxj}(t) = \sum_{\forall N_{ki} \in N_k} CD_{ki}^{maxj}(t) \qquad \text{Equation 17}$$

In order to track changes occurred in infrasystems in terms of resources consumed, generated, flowed, and capacity expansions in the infrasystem *k* for resource $\mathrm{r_j}$, we define the following ***metrics of changes*** for aggregated resource consumed, aggregated resource supplied, aggregated edge flow, and capacity functions:

$$RCC_k^j(t_2, t_1) = \frac{ARC_k^j(t_2)}{ARC_k^j(t_1)} \qquad \text{Equation 18}$$

$$RGC_k^j(t_2, t_1) = \frac{ARG_k^j(t_2)}{ARG_k^j(t_1)} \qquad \text{Equation 19}$$

$$EFC_k^j(t_2, t_1) = \frac{AEF_k^j(t_2)}{AER_k^j(t_1)} \qquad \text{Equation 20}$$

$$capacity\ function\ chanage(t_2, t_1) = \frac{capacity\ function(t_2)}{capacity\ function(t_1)} \qquad \text{Equation 21}$$

Next to the metrics of change mentioned above, we define *aggregated unavailability* to represent the effect of the major investment in the functional availability of the infrasystems. This is the total amount of unavailability of all components of the infrasystems.

Similar to sub-system metrics, we define the metric ***capacity margin*** introduced:

$$CM = \frac{Capacity\ functions - Aggregated\ Utilization\ functions}{Capacity\ functions} \times 100 \qquad \text{Equation 22}$$

Where CM is in percent, and *aggregated utilization* functions are aggregated resource supplied, aggregated resource demanded, and aggregated edge flow, which correspond respectively to their *capacity functions*: aggregated capacity of generation, maximum aggregated capacity of demand, and aggregated capacity of flow.

The amount of investments in infrasystems that leads to change the state of operations related to resource r_j is defined as the ***cumulative investment*** in million euros (Tran et al. 2016). Cumulative investment for an infrasystem should not exceeds the *infrasystem budget*.

So far, all mentioned metrics all within the control of the infrasystems and are considered internalities. Other factors influencing or are influenced by the performance of the infrasystems are grouped as externalities as they influence infrasystems from out of their boundaries. For instance socio-economic changes, influence resource capacity generations, due to increase in resource demand. Among different external factors, based on literature (Hall et al. 2016; Hall et al. 2016; Hickford et al. 2015; Lovrić et al. 2017; Thoung et al. 2016), we group ***external metrics*** a collection of required metrics to measure the following external factors:

1. *Socio-economic: gross added value (GDA), demographic changes*
2. *Environmental:* CO_2 *emission*
3. *Pricing*: Price of resources that are determined externally and influence resources involved in infrasystem processes. For instance, vehicle fuel price affects costs associated with transportation and hence freight transportation. In this framework we include fuel and energy price, next to usage fares.

These factors should be present in estimating resource demand and generation of infrasystems. Moreover, changes in the external metrics in time should be understood via existing models of fit-for-purpose models. Thus, capturing dynamic interaction between the external metrics and infrasystem performance. At the end, the ***sector-specific metrics*** defined for sub-system section should be demonstrated in the aggregated level, for infrasystems.

MODELING AND SIMULATION

In this stage, we aim to introduce sector-specific investments based on the formalized components mentioned in the abstraction stage. Next to that, this stage further describes a framework to develop an agent-based model to assist decision-makers to identify joint investment opportunities in an explorative manner. The model description follows the ODD (Overview, Design concepts, Details) protocol (Grimm et al. 2006; Grimm et al. 2010). ODD is developed to create a standard format, by which various ABMs can be described, documented, and easily be replicated (Grimm et al. 2010). In total, we describe the ABM in five elements, which is aligned with ODD protocol.

Before discussing the details of the framework in this stage, we define *observer* as a high-level controller that impose changes to the modeled entities. Observer performs activities that need higher-level of decision-making than the modeled entities. In this research, we assign the role of the observer to the user, who is a decision-maker in infrastructure agency who uses the model.

SECTOR-SPECIFIC INVESTMENT DEFINITION

In general, we identify three types of infrastructure investment, based on the introduced changes on the involved infrastructures:

1. *Maintaining sub-systems (Replacement and Maintenance)*: This type of investment is performed to enhance the deteriorated performance of the infrastructures to the initial designed performance.
2. *Upgrading sub-systems:* This type of investments extend the performance of the existing infrastructures, for instance by increasing the capacity functions.
3. *Creating new sub-systems:* New sub-systems of infrasystems will be created to enhance the performance of the existing functionalities of infrasystems (e.g. creating new railway tracks). Moreover, new sub-systems can be created to enhance the performance by adding a new functionality to the system, such as providing the ability of the railway system to generate and store electricity, sufficient to power trains in a certain trajectory.
4. *Combined investment:* It is often the case that the investments are a combination of the above-mentioned types.

In this step, we identify the *involved infrasystem sub-systems*, that are directly under the investment, next to the *starting time and duration of the investment*. It is important to *specify the location and the area* as precise as possible, where the activities of the investment take place. This can sometimes be attained by receiving spatial data from the infrastructure agencies. It is of importance to identify the technical *added values of the investments* in terms of the enhanced metrics related to *supply, demand, capacity constraints, resource flow, and externalities*.

Investments are introduced probably due to the estimated change in the demand patterns that require enhanced performance. These estimations about changes in demand should be also reflected in the model, when observer introduces the investments. This can be done by changing variables that influence both internal factors such as resource demand and edge flow, as well as external metrics such as demographic changes. Another important information is an estimation about *the amount of investments*.

In gaining required data, limitations may arise such as confidentiality issues, and uncompleted documentation, which hinder us to reach required investment details. We propose to gather missing information from the already executed investments, with similar scale and aimed added values to the considered investment. In the next step, we describe how investments should be introduced using model entities attributes.

AGENT-BASED MODEL ELEMENTS

In this section of the framework, we define elements of an agent-based model (ABM), which is at the core to bring insights on the possible effects of sector-specific investments. These elements of ABM contributes to understand the behavior of infrasystems through agents that emulate sub-systems, and are interacting with one another based on the identified and formalized interdependencies. ABM does not limit decomposing infrastructures into any aggregation level, from infrasystems to components, which provides a flexible modeling framework (Oliva et al. 2010).

1. Purpose

The model purpose is mentioned in the previous section, we aim to assist decision-makers in (i) mid-term and long-term infrastructure planning, (ii) exploring the emergent state changes of infrastructure because of sector-specific investments, and (iii) identifying investments upon which they can form cross-sectoral resource alignment and integration.

2. Agents, state attributes, and scales

An agent is a distinct entity that behave and interact as a unit with other agents, and is affected by the external factors. In this framework, we define agents, as technical sub-system components, which are represented by sets of nodes and edges for each infrasystem of N_k and E_k. States attributes are variables that distinguish agents from one another, by which we can trace changes in the agents (Grimm et al. 2010).State changes are triggered by introducing the effect of sector-specific investments to the agents. Time is modeled as discrete steps of 1 year. We propose to set the time horizon of 2030, to introduce sector-specific investments, and with regard to the influence of the investment, we run the model until 2070. Table 1 further describes agents and their state attributes, based on the entities and concepts formalized in the abstraction stage.

Table 1: Agents and state attributes

Agents	**Representation**
Consuming Nodes	Φ_k
Supplying Nodes	Θ_k
Intermediary Nodes	Ψ_k
Intra-system Edges	E_k^j
Inter-system Edges	E_{kl}^j
States of the agents	**Representation**
Accommodating System	S_k
Sub-system type (Asset type, node and edge)	Su
Set of exchanged resources	R_k
Primary resources	Rp^q
Resource Demand (node agents)	RD_{ki}^j
Resource Supply (node agents)	RS_{ki}^j
Capacity attributes:	
Minimum Demanded Capacity (node agents)	$CD_{ki}^{min\,j}$
Maximum Demandable Capacity (node agents)	$CD_{ki}^{max\,j}$
Capacity of Generation (node agents)	CG_{ki}^j
Capacity of Flow (edge agents)	$CF_{ax,by}^j$

Capacity Margin	CM_k^j
Edge Weight	$\beta_{ax,by}^j$
Age (node and edge agents)	LPI
Critical age	LPI^{max}
Unavailability (node and edge agents)	Tu
Spatial	*Location, spatial boundaries, activity buffer zone*
Upgrading cost	C^j
Sector-specific attributes	$A_k^{RD}, A_k^{RS}, A_k^{C}, A_k^{EF}$
Environment (externalities)	**Representation**
Gross Added-Value	GDA
Demographic change	*Population growth*
Environmental attribute	CO_2 *emission*
Pricing attribute	*Fuel prices* *Usage fares*

As it is mentioned in the table above, agents have spatial attributes, with geographical interactions with each other. Hence, it is of importance to represent the spatial data of the agent, and track their spatial interactions. Many ABM software have the possibility to couple GIS with ABM environment (e.g. NetLogo and AnyLogic) (Abar et al. 2017). Thus, this framework proposes to use relevant extensions of ABM software to be able to couple spatial data and interactions of the agents. Spatial states are introduced to the ABM environment will be processed and introduced to GIS extensions through functions, coupling these environments to each other. These spatial data inputs are *agents' location and spatial boundaries* that define the space occupied by the agents.

Furthermore, we introduced *activity buffer zone* that is the space around the assets involved in a maintenance, expansion, or upgrading investment. This represents the space that the investment activities take place and physically can influence the surroundings. Spatial boundaries and activity buffer zone should be introduced in a radius that become spheres around node agents, or cylinders along the length of edge agents. The introduced spatial states will be used in further steps to calculate the *spatial overlap* which is the sum of the volume that is derived by colliding the activity buffer zone with the spatial boundaries of the agents. This will be calculated by processing spatial data in the GIS extension of ABM environment.

Finally, upgrading cost is defined as a state of an agent that is not defined in the abstraction stage. This refers to a set that estimates the costs of expanding the agents' capacity attributes for the resource r_j. In the case that a new agent is introduced in any time step of running the model, C^j along with other agent states should be input by the user. Depending on the type of the agent, upgrading cost is stated per unit of resource generation, length, area, or volume. For example, the upgrading cost for electricity generation plants is stated per kW, while for laying cables under ground is per m.

3. Process overview and scheduling

In this step we aim to describe *who does what in which order,* and *when which sates are updated*. determine the behavior of the agents, or in the other words, set of rules through which the state of the agents are updated (Van Dam et al. 2012). In reality, events may occur in parallel, but in the ABM, events are captured in orders. Agents interact in the following order within each time step.

1. **Observer introduces investments**
   Based on the information gathered about sector-specific investments, the observer modifies the states of the agents to incorporate investments. We propose to create *a graphical user interface (GUI)* to select type of investment, and fill required information needed for each type of sub-systems and related states. In the GUI, there should be fields that provide the opportunity for the observer to introduce new states, or new attributes by using existing states. This becomes crucial in introducing upgrading and new construction investments, which state changes should be introduced in terms of the existing states (capacity attributes or sector-specific metrics) or creating new states, when new functionality is created that is not known within the existing agents. In Table 2, we determine required information to introduce different types of sector-specific investments.

Table 2: Introducing investment types to the model

Investment type	**Metrics to change, sub-systems directly under investment**
Maintaining sub-systems	1. Observer defines in GUI the following information: a. *Estimated start time* of the activities b. *Estimated duration* of the activities c. *Estimated capital invested* d. Involved agents by inputting *Location (coordination)* e. *Activity buffer zone* around the involved assets. 2. Agents create *activity buffer zones* around involved assets. 3. Agents reset *asset-age* (LPI) to 0, at the end of the activities. 4. Agents update days of *Unavailability* (data 1.a and 1.b) 5. Investments are saved in the *introduced investments* list to include investment information (a-e).
Upgrading sub-systems	1. Observer defines in GUI the following information: a. *Estimated start time* of the activities b. *Estimated duration* of the activities c. *Estimated capital invested* d. Involved agents by inputting *Location (coordination)* e. *Activity buffer zone* around the involved assets. f. *Update aimed level of states* based on the investments goal, e.g. capacity attributes, sector-specific metrics 2. Agents create *activity buffer zones* around involved assets. 3. Agents update capacity and sector specific attributes to the new levels (data 1.f). 4. Investments are saved in the *introduced investments* list to include investment information (a-f).
Creating new sub-systems	1. Observer defines in GUI the following information: a. *Estimated start time* of the activities b. *Estimated duration* of the activities c. *Estimated capital invested* d. Assigning *Location (coordination)* to the agents involved in the investment. e. *Activity buffer zone* around the involved assets. f. *Assign states to the new agents*, mentioning components' type (node or edge). Where new agents have sub-system type *Su,* new to the model, observer should define relevant

	states by using the available states in the model, or defining the new ones. g. *Assign aimed level of states*, e.g. capacity attributes, sector-specific metrics for new agents. 2. Agents emerge based on defined types and location. 3. Agents with priory known type of sub-systems inherit and update states, defined in the model, based on 1.g. 4. Agents with new type of sub-system create new states and sector-specific attributes (1.f and 1.g). 5. Investments are saved in the *introduced investments* list to include investment information (a-g).

In reality, the duration of the investment activities or projects fluctuates. Current framework neglect these fluctuations and this can be covered in the future works. In the case of missing data about sector-specific investments, observer should input best guesses in collaboration with experts of the infrastructure agency.

2. Investment emergence trajectories

Sector-specific investments introduce new network topology configuration and flow characteristics, which influence the interactions among agents and environment. In general, we categorize the emergence of the new investments in three trajectory. In reality, they may occur in parallel, but in ABM, agents interact in each time step in the following order.

2.1. Exploring required connectivity:

First model estimates the resource demand of all agents (step 1). When investments are introduced to the network, agent states are updated or created. There might be the case that a new agent (N_{by}) demands resources. If in the investment introduction step, the new agent is not assigned to source nodes, this step detects the *suitable* source nodes for the new agent to provide yearly resource demand RD_{by}^{j}(step 2-4). After identifying the suitable resource nodes, they are connected through straight edge agents to flow demanded commodity. Connections provided between suitable resource nodes and the new agent (as the sink node) are saved as an emergent investment in *emergent investment list* (step 5). At the end model updates the infrasystem budgets (step 6).

The following steps explain how investments are detected in the trajectory of exploring required connectivity.

1. Assigning the estimated resource demand to the new agents as well as all other agents.
2. Estimating the *area of influence* of each source node through the Voronoi algorithm, which decomposes the region under study among existing resource nodes based on distances to the nodes.
3. Identifying the area of influence in which the new agent is situated.
4. Selecting *prospect source nodes* whom area of influence share vertices with the area detected in step 3.

   Defining *suitable source nodes* (Θ_p) as a set of prospect source nodes that have the capacity to individually or collectively deliver the extra load of the new agent (N_{by}). In the other words, $\sum_{\forall N_{ax}\in\Theta_p} CG_{ax}^{j}(t) - RD_{by}^{j}(t)$ should be minimized.

The objective function finds Θ_p which provides the amount of resource close to the preferred resource demand (defined in the step investment introduction, Table 2). Based on the work of Arbelaez et al. (2014), we propose a constraint-based local search in defining suitable source nodes. This algorithm in its each iteration, selects a random node from the set of prospect source nodes, calculates the objective function, and update Θ_p for smaller values of the objective. In the algorithm, there should a procedure be defined to perturbs the solutions in the case of observing local minima. The algorithm stops after 30 runs.

5. Saving *emergent connectivity investments* in the list of emergent investment, which includes Θ_p nodes, emergent edges ($e^j_{ax,by}, \forall N_{ax} \in \Theta_p$), corresponding state change metrics, estimated costs of emergent investment, time step of emergence of the detected investment, spatial overlap, and triggering investment. The costs of emergent connectivity investments will be calculated by the taking into account the upgrading costs of all emergent edges and the sum of their lengths. Triggering investment is the sector-specific investment introduced in step 1 that led to the existence of the new agent N_{by}.
6. Updating infrasystem budgets.

2.2. Exploring demand-capacity constraints, no competition:

After allocating the suitable source nodes, first the model runs all the non-competitive agents (step 1) to track the violations of demand or capacity margins or attributes (Table 1), and saves relevant information to the *violated constraint* list, when it detects such cases (step 2). Then the model estimates the *emergent agent expansions*, and saves them as *emergent expansion investments* in the list of emergent investment (step 3). The violated constraint list is updated (step 4) and finally, the model updates the infrasystem budgets (step 5).

The following steps explain how investments are detected in the trajectory of exploring capacity constraints for non-competitive agents.

1. Model starts to run for the agents among which there are *no competitions* to supply demanded resources. For example, consider the situation where providing electricity for powering railways is only feasible through a certain electricity provider, and not through decentralized sources of energy owned by railway infrasystem. Then electricity can be provided only by one infrasystem. The number of iteration for allocating demands and supplies should be chosen to cope with the intensiveness of calculation time.
2. Whenever an agent violates a constraint, involved agents, type, the amount of attribute violation, corresponding state change metrics, frequency and time steps of occurrence are saved in a list, called *violated constraint*.
3. Then the model estimates the amount of attribute expansion to eliminate violations. Here there is no difference between extending the existing and creating a new agent (sub-system), as the amount of the estimated expansion of the agent demonstrates an aggregated value that is required to be added to cope with constraint violation.

   The detected expansion is considered as an *emergent expansion investment*, and is added to the list emergent investments including: involved agents, corresponding state change metrics, estimated costs of emergent investment, time step of emergence of the detected investment, spatial overlap, and triggering investment.

4. Violated constraint list is updated by adding the identifier of the corresponding emergent expansion investment. This list provides the overview of the occurrence frequency of the agents' constraint violations, as well as taken measures. This can inform decision-maker for example to understand how beneficial the measures were to prevent multiple capacity violations of a sub-system.
5. Model updates infrasystem budgets.

2.3.Exploring demand-capacity constraints, with competition:

Now the model runs all *competitive agents* (step 1) to track the constraint violations, and saves relevant information to the *violated constraint* list, when it detects such cases (step 2). In the next step model *detects the competitive agents* (step 3), and estimates a list of *emergent agent expansions* (step 4). Thereafter the *expansion option assessment* takes place to enable the observer to compare expansion options (step 5). Based on the provide assessment information through a model GUI, the observer *selects the expansion option* (step 6), and the option is saved as an *emergent expansion investments* in the list of emergent investment (step 7), the violated constraint list is updated (step 8) and finally, the model updates the infrasystem budgets (step 9).

The following steps explain how investments are detected in the trajectory of exploring capacity constraints for competitive agents.

1. Model starts to run for the agents among which there are *competitions* to supply demanded resources. For example, there is a competition among road and railway infrasystems to provide freight transportation for a container terminal of a port. Competitive agents cannot be edges as they are directed edges between only two nodes. Thus, the edge capacity constraints get influenced directly by the two connected nodes.
2. Whenever an agent violates the defined constraints, relevant information (see step 2 of the trajectory2.2) is saved in at the violated capacity constraint list.
3. Model *detects the competitive agents*. If the node agents that reached a constraint violation on the demand side (agent under pressure), it means that there is the possibility that they can rely on alternative agents (competitive agents), to receive a specific resource (r_j). Those competitive agents are detected through the ingoing edges that demanding nodes can receive r_j.
4. In this step, model estimates the *emergent agent expansions* based on two sets of option: equally distributed expansions and full expansion of each of the competitive agents, in a way that no constraint is violated for the competitive agents and the edges responsible to flow r_j.
5. In the expansion option assessment step, estimated costs, CO_2 emission, as well as the possible spatial overlaps. We assume the full capacity utilization for the processes that emit CO_2 for estimating the emission.
6. In this step, observer selects the preferred expansion investment by comparing between the effects of the evaluated options.
7. The detected expansion is considered as an emergent expansion investment, and is added to the list emergent investments including relevant information mentioned in the step of 4 the trajectory 2.2.

8. Violated constraint list is updated by adding the identifier of the corresponding emergent expansion investment.
9. Model updates infrasystem budgets.

2.4. Exploring for concurrent investments:

It can be beneficial to align certain activities and arrangements for planned or emergent investments to temporal and spatial proximities. These alignments and arrangements can reduce costs, facilitate planning, processing required procedures, and execution of these investments. Thus, this step seeks to reveal the possibility of alignment among planned and emergent investment to the observer, which aims to give insight about the possible collaborations with other infrastructure agencies (steps 1-2). Moreover, in this step, we also provide the possibility to suggest maintenance activities for the agents that have spatial overlap with the agents involved in a planned or emergent investment (steps 1 and 3). This gives the flexibility to consider maintenance although the agent is not at its end of life cycle, to benefit from the possibility of investment alignment with the concurrent investments. The suggested maintenance investment can change into a replacement investment with increased performance (step 4). It enables more efficient agent replacement by considering its future performance limitation. Finally, the model updates the infrasystem budgets (step 5).

The following steps explain how investments are detected in the trajectory of exploring concurrent investments.

1. First each agent involved in an investment, seeks in its close vicinity for spatial overlap with (i) other involved agents in investments, or (ii) for agents within the 90% of LPI^{max}.
2. Then if there was any spatial overlap between agents involved in investment, the following information will be saved in a new list of *investment alignment*: involved assets and their corresponding investment identifiers, time steps of planning overlap, location of the overlap, spatial overlap, and accommodating systems.
3. If there were agents in their 90% of LPI^{max}, *emergent maintenance investments* are detected and will be added to the list emergent investment including relevant information (step of 4 the trajectory 2.2).
4. For the emergent maintenance investments, when their flow, supply, or demand attributes are within the 10% of their stated limits values, the investments become emergent expansion investments. The amount of expansion will be asked from the observer, as it is a context dependent issue and can be suggested based on the infrasystems' internal goals. These investments will be also added to the list emergent investment including relevant information (step of 4 the trajectory 2.2).
5. Model updates infrasystem budgets.

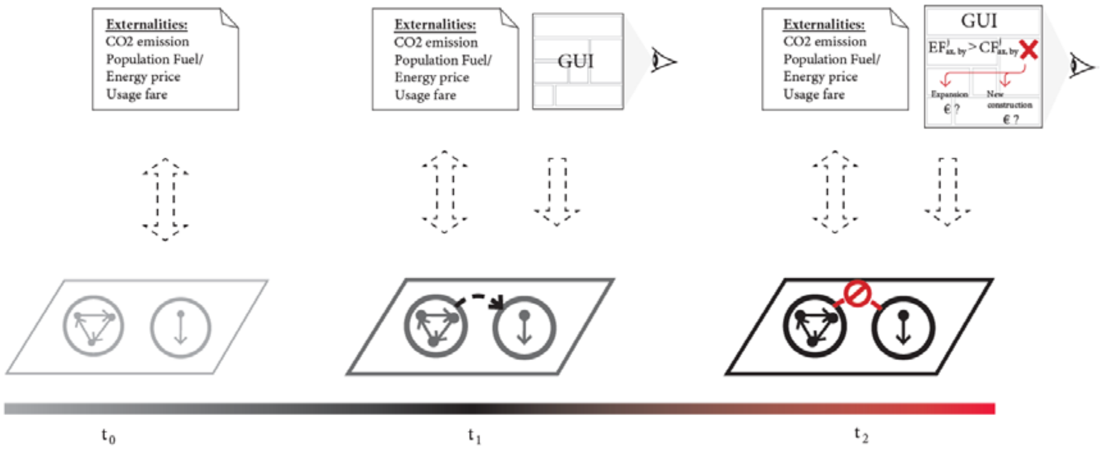


Figure 5: Conceptual example of the step of investment emergence trajectories

4. Emergent investment

In the previous step, we described how agents interact with each other, their environment and the observer. Dynamics shaping from topological and flow-based changes due to introducing planned investments, variations in external attributes, and time dependent states of agents, result in emerging the need for investment. These investment detected in the framework are arising from *conditions imposed by capacity attributes, temporal and spatial proximities*. In the framework that we presented here, the model observer has the possibility to compare the estimated performance of investments when there are competition in resource delivery. This provides more informed choices, because they can incorporate preferences of the decision-maker (e.g. evaluating between cost, emission and spatial overlap of two suggested investments). Moreover, observer can assist model by elucidate certain context dependent parameters, such as the amount of capacity attribute expansion.

In this step, we describe how to detect emergent investment and through which metrics, we can gain more insight on the performance of the infrasystems under the chosen investment pathways. That is through the information of two lists of *emergent investments* and *investment alignments* that decision-maker can establish informed cross-sectoral alignments in different processes, which can shape joint investments.

Emergent investment list contains all emerged investments, including their involved agents, corresponding state change metrics, estimated costs, time step of emergence of the detected investment, spatial overlap, and triggering investment. It is important to measure the performance of the infrasystems under the explored investments. The change metrics assist us in this matter and can demonstrate the change in resource demand, supply, capacity attributes and margins, life-cycle performance indicator, and Unavailability. For change metrics, we need to input two points of time t_2 represents the time that the suggested investment is functional for an agent, and t_1 is the time before starting the investment activities. For example, we can track the change in the capacity of flow (*CFvar*) after the capacity of a railway track is increased. Change metrics assist decision-makers to compare different investment pathways, at different decision points of the model.

Another metrics that bring insight on the performance are the metrics mentioned for the infrasystem level. These are aggregated demand, supply, consumption, Capacity Margin, Cumulative investment, and external attributes (e.g. emission). These metrics can also be a basis to compare different investment pathways in infrasystem level in a certain period. The model demonstrates the amount of investment per year and presenting the infrasystem level metrics by distinguishing between the influences of planned or emergent investments.

Insights from the cross-sectoral alignment and collaboration also comes from the information included in the list of investment alignment, which are involved assets and their corresponding investment identifiers, time steps of planning overlap, location of the overlap, spatial overlap, and accommodating systems. It provides insight about the *when to align what with who*, which enables decision-makers from different infrasystem agencies detect joint investment opportunities.

5. Input data

Input data for this framework comes from the following sources:

1. Resource demand and generated data are necessary to setup underlying models of resource demand. For instance number trains commuted between stations of a region, is used to estimate the station demands on the number of trains. We will discuss the underlying models in the following step.
2. Relevant information and geo-spatial data of the involved types of sub-systems, as well as sector-specific investments, to introduce planned investments. Estimated costs of expansion per type of sub-system should be provided with consultations of the infrasystem experts.
3. Information about sector-specific attributes, and aimed state levels of the sub-systems involved in the model as agents. For instance, maximum capacity of an edge flow.

6. Sub models

Sub models play an important role in this framework. Resource demand functions are one of the important metrics that should be determined by models within different infrasystems. In the context of interdependent infrastructure, these demand functions should include *cross-sectoral attributes*, which represent their interdependencies. These cross-sectoral factors are defined in this framework as the costs of using a service. This can be the price of the resources generated or consumed by on infrasystem, or resistance in using links of the infrasystem. The latter can represent the resistance of the cables in electricity network, or travel time in road infrastructure. Taking into account the cost function of one sector in determining the demand of the competing infrasystem, we have incorporated the cross-sectoral attribute (Blainey et al. 2012; Lovrić et al. 2017). Furthermore, demand functions should reflect their relation to the capacity of the sub-system. There we can trace the influence of different investment strategies more in a realistic manner, when considering the effect of an increased capacity on the demand. In addition, external variables (in this framework socio-economic) affect the resource demand of infrasystems, which should be represented in the models used for yearly estimation of demand. These external variables change in time, and it is important to incorporate models to track the yearly trends of these variables. Another key variable that plays a role in modeling interdependencies is the transform resource function, which estimates the generated amount of resource of an infrasystem by receiving another type of resource. For instance, the function that calculates the amount of electricity power required to power certain amount of trains. The transformation functions should be provided to be able to model the interactions among different infrasystems, and bring insight on effects of sector upon each other.

CONCLUSION AND FUTURE WORKS

In this research, we developed a framework to assist decision-makers in mid-term and long-term infrastructure planning (i) explore the emergent state changes due to introducing sector-specific investments, and (ii) identify investments upon which they can form cross-sectoral alignments. The framework assists researchers and practitioners at its core to develop an agent based model, with network representation of infrastructures as nodes and edges. This modeling framework enables us to introduce sector-specific investments using geo-spatial data, which takes into account geographical and physical interdependencies next to the functional interdependencies. As a result, the framework enables considering the different types of interdependency that can reveal more opportunities when planned investments are introduced. We introduced sector-specific investments in three main groups: maintaining, upgrading and new construction of sub-systems, while cross-sectoral interactions among infrasystems can be modeled through proposed metrics or agent states. The extent of our understanding from the infrasystems' interaction however is sensitive to the availability of the data required for introducing planned investments and attributes of the sub-system components.

So far, investments suggested based on spatial interactions are identifying the spatial overlaps of sub-system components, which is based on the estimated spatial boundaries of sub-systems and activity buffer zones. These two spatial attributes, depend on several factors, for example, activity buffer zone depends on type and stage of activities within an investment. However, on the larger scales such as national level, we need simplified and generalized assumptions to get insight on spatial interactions with minimum input required to make such assumptions. That is why this framework requires estimation for spatial boundaries and activity buffer zones (per type of investment) for agents, but are necessary to understand spatial interactions. Generally, data availability is one of the concerns in modeling interdependent infrastructures (Ouyang 2014; Saidi et al. 2018). Hence, it requires efforts to closely collaborate with infrastructure agencies to acquire as much data as possible required for the modeling steps.

Moreover, suggested investments are indications of what the possible infrastructure development pathways would be. If the focus is intended to be on the individual suggested investments, they should be further scrutinized, by increasing the level of aggregation and including more details in the environment. At higher levels (e.g. national) however, it can provide insights on the effects of planned investments on the performance of the infrastructures, and detecting the directions of the emergent investments in long term.

In this framework, observer plays significant role in shaping future development pathways by selecting among options for competitive emergent investments for infrasystem expansions. In this manner, the behavior of a real decision maker is included in a simulated process, which makes the integrated process more realistic. This can provide more informed choices, because they can incorporate preferences of the decision-maker. Furthermore, observer can assist model by elucidate certain context dependent parameters, such as the amount of capacity attribute expansion.

This framework provided sequences that agents perform certain behavior. As this model is an exploratory model, any other sequences have decisive influence on the suggested investment pathways. Hence, an extension to the current framework can be randomizing the order of interaction sequences, so that no preference is put upon specific groups of agents. Another important extension to this framework is to explore the influence of the modelling variables' change -within ranges- on the performance metrics. Consequently, the uncertainties associated with certain variables (e.g. duration of investment execution) will be considered and possible ranges of outcomes can be explored. Moreover, this enables us to set the boundaries of the model within which it works. In the other words, a range where the showed aggregated behavior of the model can be explained. An example of the variables that can be explored is the share of the competitive infrasystems in providing required capacity.

Interdependent infrastructure systems are not limited to the technical system. In the future works, we aim to incorporate social entities in the simulation who interact based on institutional ruleset of different infrasystem. This enable us to model interactions that are more complex in the context of socio technical interdependent systems. Moreover, the proposed framework needs to be validated by a real case study, which is in the scope of the future work.

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