Environmental impact evaluation using an agent based simulation framework

M.J.T. Schroyen,* M.J.L. van Tooren[†]

Delft University of Technology,

Faculty of Aerospace Engineering,

Department of Aerospace Structures and Design Methodologies,

P.O.Box 5058 2600 GB, Delft, The Netherlands

Environmental issues play an increasingly important role in aviation, affecting the desirability of novel technologies directly. The desirability of a certain technology with respect to environmental issues is determined by the system of systems level impact instead of the often used system level impact. Changing this perspective introduces additional complexities in how the system level evaluation should be related to the desired system of systems (SoS) level evaluation. A framework is proposed, using agent based simulation, to evaluate the emergent behaviour of the intertwined stakeholders and the subsequent impact of the novel technology. The Maglev assisted aircraft launch system is considered as a test case to evaluate the complexities arising in the proposed approach.

The three evaluated scenarios showed a large behavioural effect on the system of systems level environmental impact. Even though data in the scenarios were assumed and behaviour simplified, the knowledge obtained by the agent based simulation improved the understanding of the mechanisms affecting the environmental impact. Finally, the modular approach allows for an extension of the framework to evaluate more realistic scenarios.

I. Introduction

Environmental issues are becoming increasingly important in aviation. There exists, however, no consensus^{5,6} on which measures should be used to achieving a sustainable future for aviation. Several measures have been identified as influencing the environmental impact of aviation: i.e. noise, local and global emissions, and land use. Technologies and methodologies are proposed to reduce the adverse environmental impact and make aviation more sustainable. To evaluate whether these technologies actually have the desirable effect on the aviation system raises two issues: which measures should be used to determine the environmental impact of aviation and how can the impact of these technologies on aviation be evaluated. The first issue is usually addressed by assuming that a sustainable aviation can be achieved by minimizing carbon dioxide and nitrous oxide emissions and noise as proposed in Vision2020,¹⁸ a European vision formulated by ACARE. Currently, the second issue is commonly addressed by equating the technology (= system level) environmental impact¹ to the aviation (= System of Systems (SoS) level) environmental impact, implicitly assuming *ceteris paribus*. This *ceteris paribus* consideration is, however, invalidated by the behavioural change of the users. Including this behavioural change to obtain a better measure for the impact of the technology is non-trivial⁷ but shown to influence the impact of the novel technology, in particular in case of increased stakeholder value.²⁰ Furthermore, improvement of conventional technologies and methodologies is considered insufficient to achieve the required decrease in adverse environmental impact caused by aviation.²⁴ Alternative/ additional operation and technology are e.g. the continuous descent approach and the Maglev assisted take-off system. These revolutionary and possibly disruptive technologies have an even more profound effect on the behaviour of the stakeholders, further increasing the discrepancy between the system and SoS impact. Little work has, been performed in addressing the evaluation of environmental impact of these novel technologies

*Ph.D. Student, M.J.T.Schroyen@TUDelft.nl

[†]Professor, M.J.L.vanTooren@TUDelft.nl

at the SoS level, including the behaviour of the stakeholders.

This paper addresses the complexity involved in evaluating environmental impact of novel technologies at the SoS level. The proposed technology evaluation framework takes into account the behaviour of stakeholders and the subsequent impact on technology impact. Taking into account behaviour requires it to be quantified. The Maglev assisted take-off system, is taken as a representative test case for the evaluation of novel technologies at the aviation level. The complexities are addressed for this particular case and extended to a more general framework for the evaluation, addressing the identified complexities.

The Maglev system and its principles are addressed, including the assumptions made in assessing the environmental impact at system level. Second the issues identified are addressed to form the basis for a general framework capable of evaluating the environmental impact of the technology at the SoS level. Third the Maglev assisted take-off system level impact analysis is extended, using the theoretical framework, in order to obtain the environmental impact including behavioural change of the stakeholders.

II. Maglev assisted take-off system

Noise and emissions have been identified as major contributors to the environmental impact of aviation, in particular near airports. One of the dominant sources of this noise is engine noise during take-off. The engine is also causing a deterioration in air quality in the airport vicinity. The noise level and emissions are mainly determined by the thrust setting of the engine. With the introduction of the large bypass engine the jet velocities have decreased, resulting in a reduction in noise production by aircraft while at the same time lowering fuel consumption.

The bypass ratio is still being increased,⁸ however, at ever greater costs, shown in the acquisition and/or maintenance costs. One of the proposed novel technologies is to assist the aircraft in taking-off, thus allowing for a reduced take-off thrust setting or even smaller engines and consequently lower noise and emissions. The proposed means of assisting the aircraft is a proven concept of the magnetic levitation (MagLev) to propel a cart along the runway, thus accelerating the aircraft to a certain launch speed (V_{launch}). Upon reaching this speed the aircraft is released from the cart and allowed to take-off. The concept is shown schematically in Figure 1.

Figure 1. Maglev assisted take-off concept.¹²

A. Technology impact assessment

Focusing on the environmental impact of the MagLev system during the operational life phase of the system simplifies the system level evaluation considerably, without compromising the generality of the analysis. At the system level the system is evaluated using a trajectory simulation tool, which is coupled to the integrated noise model (INM¹⁰) and an emission evaluation as shown in Figure 2. For the sake of argument the trajectory is assumed to be two-dimensional.

AIRCRAFT The aircraft used in the simulation is the Boeing 737-800 with CFM56-7B26 engines, which was chosen based on availability of data. The aircraft is represented by a point mass model for the trajectory calculation. The equations of motion are based on the assumptions that 1) no wind vector is present, 2)

Figure 2. Coupling of the impact analysis and trajectory simulation modules to determine the MagLev impact at system level.

the earth is flat and non-rotating and 3) the flight is coordinated. Furthermore, a standard atmosphere is assumed as well as a constant aircraft weight, W , during the climb. Finally, the aircraft is assumed to be controlled by the thrust setting Γ and flight path angle γ at zero bank angle $\mu = 0$,

$$\begin{aligned}\dot{x} &= V \cos \gamma \\ \dot{y} &= 0 \\ \dot{h} &= V \sin \gamma \\ \dot{V} &= \frac{T(\Gamma) - D}{W}\end{aligned}\tag{1}$$

DEPARTURE As a reference departure the NADP-1¹³ departure procedure was used. The considered trajectory is limited to an altitude of 3 kilometers. The conventional take-off was modified accordingly for the MagLev assisted take off:

- Flaps were retracted
- the launch speed (V_{launch}) was increased from the conventional $97m/s$ to $150m/s$
- the thrust was allowed to vary between 0 and 100% of the take-off thrust.

The MagLev trajectory was defined as the part of the departure after release from the cart and rotation of the aircraft, whereby the aircraft follows a path with a flight path angle of 7.4° and constant thrust setting. Once the velocity decreased below the threshold of $100m/s$, the NADP-1 procedure, both flight path angle and thrust setting, for that altitude was employed. This approach resembles the strategy of increasing altitude as quickly as possible using the kinetic energy in the aircraft obtained from the MagLev system.

ENVIRONMENTAL IMPACT The resulting aircraft trajectory are fed into the INM and Emission evaluation to determine the noise contours and emissions during take-off. The INM¹⁰ requires the aircraft trajectory and thrust setting, as a set of intermediate points, to determine the noise on a grid point. The emission analysis consisted of an interpolation of emission databank¹⁴ data. One point in particular is considered for the use in the system of systems analysis to evaluate the effect of the MagLev system on the environment. This point is located, somewhat arbitrarily, on coordinates $[X, Y] = [10, 0]$.

B. Results

The noise contours for three different thrust settings and the NADP-1 departure are given in Figure 3. Comparing the zero thrust setting to the NADP-1 contours, a reduction close to the runway can be identified and an increase in noise at $[X = 6]$. The decrease is caused by the larger initial launch speed and lower required thrust setting. However, due to the zero thrust setting the aircraft reaches the threshold velocity of $100 m/s$ rather quickly and has to increase thrust setting to the one determined by the NADP-1 procedure, resulting in the sudden increase in noise level. With increasing thrust setting this phenomenon decreases at the cost of increased overall noise. The effect of the Maglev system on the maximum A-weighted noise level ($L_{A,max}$) for various thrust settings in the control point are shown in Figure 4(a). For a thrust setting of 0.4 the A-weighted maximum noise level results in the minimum noise level.

Figure 3. Noise contours and location of test point.

Figure 4. System level environmental adverse impact reduction due to the Maglev system.

For the carbon emissions, both the fuel flow with thrust setting and the time to climb are important. Due to the increased initial speed the time to climb is decreased considerably, even though the fuel flow is higher. The results are shown in Figure 4(b) minimal for the simulated trajectory. In conclusion, at the systems level the noise contours and emissions can be influenced by employing the Maglev assisted take-off system. Furthermore, the environmental impact at take-off can be reduced by using appropriate thrust settings. Even though this is probably not the most optimal take-off procedure achievable it will be used in the coming sections.

III. SoS level impact

In order to determine the system of systems (SoS) level impact of the Maglev assisted take-off system from the previously derived system level impact, multiple take-offs and their effect on environmental impact have to be considered. Example measures are 1) awakenings,¹¹ to include the effect of population distribution on annoyance near the airport, and 2) Kosten levels, to determine the annoyance caused by a certain sound level.¹⁹ Since no population distribution is available, Kosten levels will be used here. In essence this inference from system level to system of systems level includes additional stakeholders to obtain a measure of desirability for the changed contours. Furthermore, the reduction per departure in noise level and emissions might be negated with an increase in allowed aircraft movements, i.e. take-offs and landings (within the noise constraints). This scenario is not unlikely as airports desire to use their expensive infrastructure to maximum capacity,⁹ directly affecting the resulting environmental impact. Aforementioned issues require an evaluation at the SoS level, to determine the impact of the technology at aviation level, including the behavioural change of the stakeholders. A framework for performing this evaluation will be presented, based on the two questions previously identified;

- What is a suitable measure for the evaluation of the technology
- How is the environment of the technology affected by the changed stakeholder behaviour

ENVIRONMENTAL IMPACT The first question raised was how to measure the environmental impact. A choice was made for noise and emissions, environmental impact is, however, a broad term in need of clarification. Environmental impact is in general defined as

a marked effect or influence of human activity on the natural world.

In this paper “marked effect or influence of human activity” is restricted to *the effect of a technology* and the “natural world” to *the natural and human environment*. In talking about environmental impact it is implicitly assumed that adverse or undesirable environmental impact is meant. As a consequence, minimization of environmental impact is deemed to result in a more sustainable aviation system. Not addressing the political issues of what is desirable and sustainable, the objectives as given in Vision2020¹⁸ are taken as a guideline

- Carbon dioxide and nitrous oxide reduction
- Noise reduction.

with the additional notion that above mentioned measures are ambiguous. Consequently, the framework should be able to handle alternatives.

CHANGING ENVIRONMENT Furthermore, the environment in which the technology operates is not constant as was implicitly assumed when using the impact per operation as a measure. This environment is not limited to the customer, therefore conventional value evaluations - QFD, Value engineering - should be expanded from a customer oriented to a stakeholder oriented perspective. A stakeholder is defined according to Freeman;¹⁶

A stakeholder in an organization is any group or individual who can affect or is affected by the achievement of the organizations objectives.

Applied to the global aviation system a large number of intertwined stakeholders can be identified, of which the most readily identified stakeholders in aviation are shown in Figure 5. The number of stakeholders and their interactions directly influence the complexity of evaluating the impact of a novel technology.²² To

Figure 5. Subjective and incomplete view on stakeholders in aviation.

address all stakeholders and their interactions would become a daunting task and beyond the scope of the paper. Even when all stakeholders are incorporated in the analysis, their respective importances have to be determined in defining the measure for environmental impact, when conflicting needs arise. Mitchell¹⁶ proposes a method of ranking stakeholders based on three attributes, *power*, *legitimacy* and *urgency*. These attributes are all relative, meaning that they are determined by the interaction between stakeholders, e.g. a stakeholder only can exert power over another stakeholder if there is a direct relation between them. Furthermore, Rowley²³ shows that one cannot merely look at the dyadic ties between the stakeholder of interest and the surrounding stakeholders in closely intertwined networks like aviation.

A. Agent based framework

As previously discussed, a framework for environmental impact evaluation should be able to handle the intertwined interaction between various stakeholders. Furthermore, it should be flexible enough to include additional stakeholders and novel technologies. The latter requirements are derived from the fact that the knowledge about stakeholder behaviour and interaction is far from complete requiring an easily adaptable (modular) framework which can handle the multitude of solutions proposed to reduce aviation environmental impact. The two analysis types, the system level and SoS level analysis, are coupled by the environmental impact at system level and the emergent behaviour at the SoS level. A schematic iterative approach is shown in Figure 6(a).

Borrowing from social studies and economics, an agent based framework¹⁷ is used as a starting point. An agent based framework consists of an environment and agents. The environment can be a (directed) network, which sets the boundaries for the agents and their interactions. The agents, on the other hand, are individual decision making entities. Within the environment these agents are allowed to interact as shown schematically in Figure 6(b). The flexibility, required for the environmental impact framework, stems from the modularity of the agent based framework. Adding stakeholders consequently implies adding classes and their interactions with the existing agent classes and environment. This makes those classes interchangeable as well, allowing for the evaluation of novel technologies.

The resulting environmental impact of the novel technology is determined by the combined behaviour of the agents. This combined behaviour is often unequal to the sum of the individual behaviours and is called *emergent behaviour*. To be able to populate the environment with agents their interaction has to be quantified. The goal of this paper is not to find the optimal strategy for an agent or the optimal procedure

Figure 6. Agent based framework.

to decrease environmental impact, but to demonstrate the principles and steps needed to evaluate the SoS level impact of a novel technology using an agent based framework. The setup of the model is treated by the following steps;

- Identification of agents and environmental parameters of interest
- Agent goal identification and strategies
- Data gathering to quantify the behaviour

B. Agent

The summation of all interactions of an agent with its environment - consisting of other agents and the environment - is called behaviour and is determined by both the information, as interpreted by the agent, gathered from the environment and the agent properties.² The behaviour is implemented within the agent as decision rules,¹⁷ which transform the input and agent properties into an output. This corresponds to the basic notion that agents behave according to incentives as is common in economics. In order to be able to implement the decision rules the information from the agents' environment has to be ordered/coded. Furthermore, the environment, or information sphere, of the agent has to be determined. In order to code the information, the concept of *utility* from micro-economics is employed.⁴ Utility or value is a general notion of the desirability of consumption of a good or service. In this context utility is broadened to the desirability of the consequences of an action for the agent. Utility thus provides measure for the desirability of the action. Consequently, various options can be ranked according to utility and behaviour can be defined accordingly,

$$B = \max_C U, \quad (2)$$

which shows in mathematical form, choose the action from option set C which maximizes utility U and act accordingly. This maximization principle is one implementation of rational decision making.²¹ The utility U and set of possible actions C are determined by the agents environment^a and agent properties.^b Restrictions on possible actions are constraints and with the assumption that behaviour maximizes utility, decision making can be written as a constrained optimization,

$$\begin{aligned} \max_x U(x, y) \\ g(x, y) \leq 0, \end{aligned} \quad (3)$$

^aIf noise constraints are reached by the airport, increasing operations is not an option.

^bThe agent might represent a customer, therefore behaviour does not include manufacturing an aircraft.

where x are the parameters which can directly be influenced by the agent and y parameters, which cannot directly be influenced. Consequently modifying x to the appropriate values is the resulting behaviour.

IV. Implementation

As an illustrative example the previously considered Maglev system is used. The focus of the implementation is on the method structure and principles required to setup the prescribed framework. The Maglev system is intended to reduce the environmental impact and as a consequence externalities^c. The focus will therefore be on the interaction between voluntary transaction and its externalities, in particular in the operation. The complexity of the actual interaction between all players is reduced by limiting the current example to the four primary stakeholders, rational behaviour and complete information.

Figure 7. Agents and their interactions shown as a network. Focus on the externalities resulting from the introduction of the Maglev system.

For the Maglev test case, the following stakeholders are assumed, the airport, airlines including their passengers and the communities living near the airport, as shown in Figure 7. The assumed goals and strategies (decision variables) for reaching them are stated in the following paragraphs.

AIRPORT The airport is assumed to be a commercial company which brings passengers and airlines together, i.e. it provides land and air based services for both passengers and airlines.⁹ The revenues and costs for an airline are based on an airline service part and a passenger part. The airline services consist of for example air traffic service provision, runway use and gate use. Costs are generally levied on an aircraft weight basis. The services per passenger consist of for example security provisions, check in desks, baggage handling, and are usually levied as a percentage of the ticket fare. As a result the profit function which is to be maximized by a single runway airport is composed of two parts,

$$\begin{aligned} \max_x \pi &= \sum_i \sum_r r_{i,r} f_{i,r} + \sum_i \sum_r t_{i,r} D_{i,r} - C \\ \sum_i N_i &\leq N_{\text{slots}} \end{aligned} \quad (4)$$

where π is profit, $r_{i,r}$ is the profit generated (e.g. revenue minus costs) per airline i per route r per flight for providing the air services, $f_{i,r}$ is the number of flights for airline i on route r . $t_{i,r}$ is the fare levied from the passengers for airport provided passenger services from airline i on route r (usually a fraction of the fare), $D_{i,r}$ is the satisfied demand and C are the fixed costs of the airport. Furthermore, the number of slots on the airport can either be restricted by technical, safety or environmental considerations. For this example it is assumed that the airport is noise constraint, i.e. the number of slots which can be allocated is restricted by noise considerations,¹⁹

$$N_{\text{slots}} = f(L_{A,\text{max}}) \quad (5)$$

^cExternalities are the involuntary costs or benefits for a third party of a voluntary transaction between party one and two. These involuntary costs or benefits are not incorporated in the voluntary transaction causing a discrepancy between private and social optimum.

The decision variables for the airport as a consequence is the allocation of this scarce resource to the various airlines. Since the largest part of the airport revenue comes from commercial activities other than air operations,⁹ the strategy implemented is to allocate the slots based on satisfied demand $\sum_i D_{i,r}$. The assumed strategy is simplified from the actual airport slot allocation procedure. This actual slot allocation procedure is often dependent on the current shareholders' goals, which might be maximizing quality of service, destination choice. Dependent on the airport and shareholder organization this might result in self-regulation by airlines or slot allocation by government or airport.⁹

The Maglev system as described in Section II was found to reduce noise and as a consequence allows an increase in maximum number of slots. The relation between the noise production and number of slots is discussed in the paragraph on the community.

Figure 8. Airline optimization problem for a single route.

AIRLINES The airline is considered to provide a transport service for passengers from airport to airport. The number of passengers which can be transported is limited by the number of seats provided $D_{i,r}^P$ as well as by the passenger demand and service (airline) preference $D_{i,r}^D$. The latter will be detailed in the following paragraph on passenger behaviour. Furthermore, the total amount of flights which can be attributed to the routes is limited by the number of slots allocated to the airline by the airport. The airline behaviour is characterized as maximizing profit by selecting the number of flights on each route,

$$\begin{aligned}
 \max_f \pi_i &= \sum_r p_r D_{i,r} - f_{i,r} C_{i,r} \\
 D_{i,r} &\leq f_{i,r} S_{i,r} = D_{i,r}^P \\
 D_{i,r} &\leq D_{i,r}^D \\
 \sum_r f_{i,r} &\leq N_i \\
 f &\in \mathbb{N}
 \end{aligned} \tag{6}$$

where π_i is the profit for airline i , p_r the fare levied for route r , $D_{i,r}$ the satisfied demand for the route, $f_{i,r}$ the number of flights and $C_{i,r}$ the cost per flight. As indicated by Wei and Hansen,²⁵ fares do not differ much between similar airline types (e.g. scheduled carrier) on a given route, as a consequence they are considered equal for this example.

The airline decision variables are the demand $D_{i,r}$ and the number of flights $f_{i,r}$ on a route by route basis. The overall optimization function including constraints is shown schematically in Figure 8. From this figure it can be seen that profit is monotonously increasing with demand for a given number of flights, $f_{i,r}$. Consequently the profit function can be maximized for a given number of flights, by minimizing spilled demand, $D_{i,r} = \min [D_{i,r}^D, D_{i,r}^P]$. Solving for $D_{i,r}$ leaves number of flights, $f_{i,r}$, as the airline decision

variable.

The previous consideration is for a single route only. To extend the optimization to multiple routes the Bellman equation for resource allocation is used and implemented by dynamic programming,³

$$\Pi(r, f) = \max_{0 \leq f' \leq f} (\pi(r, f') + \Pi(r - 1, f - f')), \quad (7)$$

where r is the route under consideration, $\pi(r, f')$ profit for the number of flights allocated to route, and $\Pi(r - 1, f - f')$ the maximum combined profit for all previously considered routes when $f - f'$ slots are allocated to them. After considering all routes $r = [1, R]$, the optimal strategy is the allocation of number of flights providing maximum overall profit,

$$\max_f \Pi(R, f) \quad (8)$$

This is procedure is performed iteratively for all airlines and routes until equilibrium is achieved^d.

PASSENGERS As determined by Wei and Hansen,^{25,26} one of the product attributes favored by the passengers is the number of flights offered. The passenger demand $D_{i,r}^D$ for airline i 's service on route r is assumed to be given by,

$$D_{i,r}^D = Q_r \frac{f_{i,r}^\alpha}{\sum f_{-i,r}^\alpha + f_{i,r}^\alpha} \quad (9)$$

where Q_r is the total demand for the route r under investigation, f_i the number of flights offered by airline i and f_{-i} the number of flights offered by all other airlines. The preference factor α as determined by Wei and Hansen²⁵ of 1.093 is used. This model does not offer the passenger an outside choice of not flying and latent demand is consequently not included. Latent demand is defined here as the people preferring to travel by air, but currently choosing alternatives due to lack of money, availability or information. In particular, the current situation takes the demand before the MagLev introduction as a maximum and distributes these passengers according to preference among airlines, spilling demand when insufficient capacity is provided. The introduction of the Maglev system, as well as change in number of flights, might change overall service preference changing overall demand by influencing the preference for the external choice^e This change in demand can be included by making the overall demand a function of the service attributes $Q_r = Q_r(x)$. This external choice effect on the overall route demand is used to include the possible adverse effect of the Maglev system on the passenger demand. The Maglev system might not be embraced by the passengers immediately. Consequently a reduction in passenger demand is therefore anticipated, these potential passengers might opt for an alternative mode of transportation, choose a different airport or decide not to travel at all.^f

$$Q_r = \theta Q_{r0} \quad (10)$$

COMMUNITY The community near the airport is assumed to have an adverse taste for the noise producing activities of the airport. The options for the community are often related to influence exerted on the service through governments and subsequently regulation. This imposes additional constraints on the options of either the airport or airline. For this example a relation between the noise production of the airport and the number of slots provided to the airport is considered, as given by the Kosten formula^{19g},

$$B = 20 \log_{10} \left(\sum_{j=1}^N w_j 10^{L_{A \max j} / 15} \right) - 157 \quad (11)$$

where the weighing factor w_j , dependent on flight time, is assumed to be 1, B is the total noise load in Ke , N the total number of movements per year and $L_{A \max j}$ the maximum A-weighted sound level for movement j . A Kosten factor B of less than 35 is considered to be the limiting total noise level found acceptable by

^dThis iterative procedure is required due to the dependence of passenger demand on the other airlines' number of flights.

^eThis change is caused by people diverting from or to an external choice, e.g. an alternative mode of transportation, a video conference or the choice for not travelling.

^fThe external choice is a change in behaviour outside the behavioural model resulting in unpredicted system of systems behaviour, i.e. unconsidered externalities.

^gOther measures for the quantification of the community's adversity towards noise pollution exist, e.g. awakenings.¹⁹ These can easily be implemented by changing the community agents maximum slot setting procedure.

the community. Furthermore, assuming equivalent noise contours per aircraft (i.e. similar type of aircraft and path), the total number of slots as a function of maximum A-weighted sound level becomes,

$$20 \log_{10} N_{\text{slots}} = B_{acc} + 157 - \frac{3}{4} L_{A \max}, \quad (12)$$

where B_{acc} is the Kosten level considered acceptable, in this case 35 is assumed. With decreasing sound levels the maximum number of slots is seen to increase. The idea that the maximum number of slots increases stems from the fact that the community near the airport derives benefits from the airport and a more productive airport increases those benefits.¹⁵

DATA the used data are listed in Table 1 and Table 2. The data are considered representative for the variation in routes and cost structures of airlines. The factor ξ is used to manipulate the overall demand to be able to generate three scenarios, 1) unconstrained by noise ($\xi = 20$), 2) intermediate ($\xi = 40$) and 3) noise constraint ($\xi = 60$). From the MagLev concept description in Section II it was derived that this system is able to decrease the noise factor between $L_{A \max}/L_{A \max 0} = [0.91, 1]$ for thrust settings between 0.4 and 1. For this range of thrust setting the carbon dioxide emission per flight is interpolated to determine the overall efficiency with respect to carbon dioxide emissions.

Table 1. Assumed airline data.

(a) Cost per flight.						(b) Seats per flight.					
AL \ Route	1	2	3	4	5	AL \ Route	1	2	3	4	5
1	7106	7904	12241	-	10794	1	140	188	140	-	188
2	-	-	12065	8814	-	2	-	-	173	157	-
3	-	-	-	3743	5807	3	-	-	-	159	183
4	7986	7960	-	3883	-	4	183	160	-	160	-
5	-	-	-	3005	-	5	-	-	-	123	-

Table 2. Assumed route specific data.

Route	1	2	3	4	5
Q_r/ξ	67	119	291	379	327
p_r	181	170	260	158	149

V. Results

Two considerations are evaluated using the three previously described scenarios: 1) the externalities and 2) the willingness of the stakeholders to invest in the MagLev system. The first subsection will focus on the environmental impact at system of systems level, whereas the second one will focus on the economic feasibility of the MagLev system.

A. Externalities

Figure 9. Externalities.

Figure 10. Resource usage.

NOISE The results in Figure 9(a) show that the decrease in A-weighted maximum noise level per flight has no one to one relation with the decrease in Kosten number. In particular, the availability of additional slots is translated into an increase in number of flights for all three scenarios. This was expected for the noise constraint ones (2,3) as the spilled demand can be decreased by increasing the number of flights and consequently increasing airline profits. The increase in satisfied demand is shown in Figure 10(a). For the non-noise constraint scenario (1), the increase in number of flights needs some elaboration since spilled demand is already zero (Figure 10(a)). An increase in number of flights can therefore only be considered worthwhile for an airline if it increases airline market share on a route, i.e. modifying $D_{i,r}^D$ in Figure 8. The resulting behaviour of the other airlines is to increase number of flights as well (within their number of slots)

to recapture their market share. The result is that airlines try to keep their same market share, and when competing airlines increase their number of flights on a route, the other airline's best response is to increase the number of flights as well. For these scenarios overall demand Q_r was kept constant, consequently the loading factors should decrease, resulting in less efficient passenger transportation.

CARBON DIOXIDE Furthermore, this increase in offered flights has a direct effect on the overall system carbon dioxide emissions as depicted in Figure 9(b). Even though the amount of carbon dioxide during take-off per flight was decreased, this effect appears to be negated by the increase in number of flights. The ratio of total slots available and total slots used, as seen in Figure 10(b), decreases for scenario 1. Since the increase in slot availability is non-linear with per-flight maximum A-weighted noise level, Equation 12, an increase in number of flights can be derived from this. This increase in number of flights is seen as the primary cause of the increase in system carbon dioxide emissions.

In conclusion, the externalities are highly dependent on the behaviour. For all three scenarios the uncontrolled carbon dioxide emission per take-off, even though decreased from a system perspective, was seen to increase. Although this is based on assumed data, this shows that stakeholder behaviour should be taken into account when considering externalities and in particular environmental impact. Although these scenarios are constructed and based on assumed data, the trend of increasing number of flights with extending noise constraints can be seen at, for instance, Schiphol.¹⁹

B. Introduction of the Maglev system

Figure 11. Effect of passenger adversity towards the MagLev system.

The second investigation performed is the stakeholder acceptance of the MagLev system in the three scenarios.

AIRPORT The primary investor, the airport, can be assumed to accept the novel technology if it increases its profit. Since profit was assumed to be dominated by satisfied passenger demand, increasing satisfied passenger demand is used as a guide for MagLev system acceptance. Figure 10 shows that for scenarios 2 and 3 satisfied passenger demand increased, whereas for scenario 1 satisfied demand remains constant. Including passenger adversity results in a factor $\theta = 0.80$, reducing overall passenger demand, scenario 1 is considered to be the scenario where investing in the MagLev system is not considered worthwhile for the airport. For scenarios 2 and 3 the balance between additional passenger revenues and costs per flight should determine whether the investment is interesting.

AIRLINE Figure 11(a) shows the overall profit for the airlines, which can be seen to increase up to the point where total demand is satisfied, after which it decreases again. This latter fact is due to the increase in number of flights (and costs) to maintain market share once the competing airlines increase their number

of offered flights as discussed in the previous section. For scenario 1, this point is reached without noise reduction and consequently decreases overall airline profit. For scenario 2, without adverse effects this point is reached at a noise reduction ratio per flight of 0.96, and with adverse effects at 0.97 as seen in Figure 11(b). As a consequence, if all demand is considered satisfied, the introduction of the MagLev system is not considered beneficial for the airlines in the current scenario.

In conclusion, if unsatisfied demand is available, additional flights allowed by the lower noise per flight production appear to be beneficial for airlines, airport and passengers. This corresponds to the trends seen at Schiphol airport (IATA:AMS), where the introduction of more noise efficient aircraft had only a small effect on the noise contours but a large effect on the number of movements performed.¹⁹

VI. Conclusion

This paper shows the difference in environmental impact at the system and System of Systems (SoS) level. This difference is contributed to emergent behaviour from the stakeholders. A MagLev system was used as a showcase for the proposed method of SoS level environmental impact evaluation of a novel technology. For this purpose an agent based simulation framework was used, consisting of airlines, passengers, an airport and community. These stakeholders, implemented as agents, were assumed to behave goal oriented and with their behaviour and strategy quantified by the concept of value (utility), discrete choice analysis, game theory and dynamic programming.

The externalities investigated are noise and carbon dioxide emissions during take-off. At the system level both noise and emissions are seen to decrease with respect to the reference NADP-1 take-off. Three agent based simulation scenarios are created; demand which could be completely satisfied, noise constraint and intermediate. In all three scenarios controlling the number of slots restricts the total noise level, but an increase in emissions is still observed due to the increase in flights. This increase in number of flights without filling more demand is attributed to maintaining market share by the airline. This shows the importance of stakeholder behaviour when evaluating the externalities at system of systems level.

Investment of the airport and airlines in the MagLev system appears only valid if additional demand can be captured, this also allows the airlines to increase profit. If passenger aversion against the MagLev system is included, overall demand is decreased and the profits for both airlines and airports are considered to decrease.

The resulting insights in trends in externalities or environmental impact could be used to adapt the requirements (objective function/ constraints) on the design or alternatively determine the requirements which result in the desired behaviour for the identification of requirements. Furthermore, a thorough understanding of the incentives of the stakeholders might provide opportunities for environmental impact reduction by correct design of the interaction of system and stakeholder.

One important aspect of this framework should be noted. The simplifications and inherent limitations to the behavioural modeling of the agents (stakeholders) restricts the forecasting capability of the framework. The implementation of the MagLev system might result in unexpected stakeholder behaviour either by changing strategies, changing goals or even the occurrence of a new type of stakeholder. One example would be that if annoyance by carbon dioxide emission (i.e. air quality) supersedes noise annoyance, slot allocation on the basis of carbon emissions would be the new strategy. Improvements in understanding (changing) stakeholder behaviour, in particular due to novel technologies, are therefore critical to addressing the behavioural complexity arising in the evaluation of the impact at SoS level.

Furthermore, to tackle the environmental issues the need is identified to broaden the evaluation of the system from customer to stakeholder analysis. This broadening was required for the Maglev evaluation since the customer view neglected the adverse environmental impact of the technology imposed on the community near the airport.

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