Proceedings of the 2018 Winter Simulation Conference
M. Rabe, A.A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, eds.

FLEXIBILITY AS AN ENABLER FOR CARBON DIOXIDE REDUCTION IN A GLOBAL SUPPLY CHAIN: A CASE STUDY FROM THE SEMICONDUCTOR INDUSTRY

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ABSTRACT

Due to the significant rise in environmental awareness of companies and customers for the past few years, research on how to optimize business with respect to carbon dioxide (CO_2) emission has gained more attention and importance. This paper investigates how flexibility can be an enabler for CO_2 reduction over a global production network especially in a capital intensive and high volatile market like the semiconductor one. We tested this hypothesis with discrete-event simulation experiments based on a case study obtained from a semiconductor company. The study indicates that global supply chains (SCs), like those in the semiconductor industry, should be equipped with a certain level of flexibility to cope with demand volatility if the CO_2 burden due to transportation is low compared to those due to manufacturing. This flexibility provides ecological benefits to companies in reducing the carbon footprint of their products.

1 INTRODUCTION

The semiconductor market is volatile and unpredictable. Therefore, the ability to forecast customer demand is limited and, in turn, the results of business operations are negatively impacted (Chou et al. 2007). Thus, semiconductor companies seek to optimize the production capacities at their in-house manufacturing sites in order to cope with these challenges (Bong and Potoradi 2000). It is well known in semiconductor manufacturing that building additional capacity incurs high capital cost, usually in the order of several billion US dollars (Brown and Linden 2005). However, flexibility is often the choice to improve the productivity of expensive equipment without further increasing capital spending. Because of the nature of the semiconductor industry, airfreight is the preferred method of transportation due to short transportation times and high value product density (Rajan and Srivastava 2007). Yet, the question that needs to be answered is whether this choice of flexibility, in the case of capacity shortage due to volatility, is beneficial from an ecological point of view. Thus, this paper focuses on this question. According to Lee (2002) and Mönch et al. (2017), the semiconductor industry is characterized by:

- A high capital cost, driven by the expensive cost of equipment and R&D facilities
- Short product life cycles due to fast technological development, as described by Moore's law
- High demand volatility due to the upstream position within the entire SC
- Long production cycle times because of up to 1000 process steps
- High energy consumption in production needed for cleanroom conditions, and
- Airfreight as a main method of transportation due to its short lead times and high value product density

These characteristics lead to a well-known phenomenon called the bullwhip effect, which is one of the challenges of semiconductor supply chains. The bullwhip effect is the amplification of the demand upstream of the SC, even if there is only a small change in the demand and sales downstream towards the end customer (Lee et al. 1997, Bray and Mendelson 2012).

The central research question of this paper is how the flexibility of a global SC enabled by a global production network could be a driver for the CO_2 reduction. The following questions contribute to answering the central question:

- What are the major drivers of the CO_2 emissions that result from producing one single product and deliver it to the customers, and the share of these major drivers in the total emission
- What kind of CO_2 emissions results from enabling flexibility in the global SC
- What is the optimized built flexibility from a CO_2 and a unit cost standpoint at a given volatility and at a given ratio between transportation and manufacturing CO_2 or cost burden

In addition to answering these questions, this paper gives a proposal for improving the study of flexibility in a global SC in a more realistic way using simulation modelling. Figure 1 shows the black-box of the simulation model for this paper. Accordingly, the simulation model has inputs of flexibility, forecast accuracy and capacity utilizations, and primary outputs of CO_2 per component and cost per component.

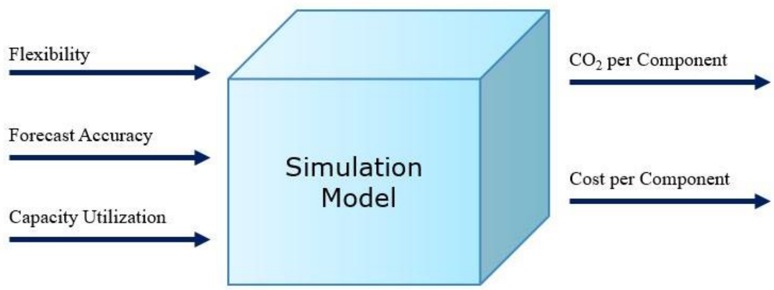


Figure 1: Black-box model of the simulation model.

This paper is organized as follows. The next section presents the related literature in Section 2, which is followed by the description of methodology in Section 3. The results of simulation model are discussed in Section 4. Finally, the paper is ended with concluding remarks in Section 5.

2 RELATED LITERATURE

Related literature is surveyed under two different parts. The first part is on the Green Supply Chain Management (GSCM) in which the definition of green supply chain and its situation in the semiconductor industry are presented in Section 2.1. The second part is on flexibility and its ecological impact on SCs where flexibility measures and a flexibility framework for the semiconductor SC are provided.

2.1 Green Supply Chain Management (GSCM)

The Green Supply Chain Management (GSCM) evolved from the conventional Supply Chain Management (SCM) field. SCM is defined as all the activities that are related to the supply of the product from the raw materials to the customers, this includes the procurement of the raw materials, manufacturing and assembly, packaging and delivery, as well as the movement of information related to these activities (Masteika and Čepinskis 2015). While Srivastava (2007) gives a classification of the GSCM based on integrating environmentally sound choices within the SC operations, Diabat and Govindan (2011) define GSCM as incorporating environment criteria within the organizational decision-making.

One of the most popular environmental criteria used in GSCM is the so-called carbon dioxide equivalent or CO_2eq, which is defined according to the UN International Panel on Climate Change (IPCC), as a basis of comparison for emissions of different greenhouse gases based on the global warming potential (GWP), and obtained by converting the amount of the specific greenhouse gas into its equivalent amount of CO_2, based on 100-year global warming potential. In the literature, only handful of scientific papers link the GSCM and the CO_2eq. Bonilla et al. (2015) use the CO_2eq as a metric for measuring emissions for offshoring manufacturing production as well as for comparing the carbon footprint of different industries such as the semiconductor industry and the textile industry. Chiang and Hsu (2017) consider the CO_2eq as an important tool for evaluating environmental policies such as carbon taxation or emission limits. Their study suggests four master planning methods with different types of taxations and their impact on reducing the emissions. Their simulation results prove that the carbon taxation is central to environmental protection. Villarreal-Singer et al. (2013) present a simple model to project the emissions from energy conversion with variety of different assumptions such as change in GDP and emission factors. Their forecasting tool has high accuracy in forecasting CO_2 emissions compared to historical data.

The field of GSCM is a recent area of research and it is less discussed in the literature. Shang et al. (2010) identify six dimensions for the GSCM. These dimensions are: (1) green manufacturing and packaging, (2) environmental participation, (3) green marketing, (4) green suppliers, (5) green stock, and (6) green eco-design. Based on these factors, semiconductor firms are classified into four groups: the weak GSCM oriented group, the green marketing oriented group, the green supplier oriented group, and the green stock oriented group. Their study indicates that the green marketing oriented group performs the best among the other categories. Other literature in the field of GSCM in the semiconductor industry is dedicated to the usage of renewables in the production of semiconductor devices. For example, Sanders et al. (2012) evaluate the performance of wafer fabs located in Texas, US and Dresden, Germany using distributed generation and photovoltaic energy. Ziarnetzky et al. (2017) incorporate elements of sustainable system in a production planning of a wafer fab, and demonstrate that it is environmentally reasonable to combine production-related and distributed generation decisions. According to Byrne et al. (2010), the reduction of the environmental impact within SCs has a payback in terms of reduced direct or indirect costs and increase in the revenue.

Based on the conclusions of Liebi (2011) and Reinhard (2011), regarding the potential of semiconductor SCs to reduce CO_2, a new area of research emerges, which is reducing CO_2 through the flexible utilization of production capacities. The work is continued by Yorck (2013) in which he simulates the SC of Infineon to test the hypothesis that flexibility enabled by a global network of transportation could have positive ecological impact. Yorck (2013) confirms the hypothesis for front-end production. There have been several issues on how to handle flexibility in this work which still needs to be overcome.

2.2 Flexibility and its Ecological Impact on Supply Chains

2.2.1 Flexibility

The term flexibility is perceived by various means in the industry, such as ability to change, responsiveness to a dynamic situation, or the level of automation (Browne et al. 1984; Vickery 1999; Manders et al. 2014). Related literature provides valuable and structured information for flexibility concept and explains why firms need flexibility. Merschmann and Thonemann (2010) state that an increase in the uncertainty of an environment leads to an increase of the flexibility level for SCs to reach high performance based on the analysis done with 85 German manufacturing companies. Also, in wafer fab level, maintaining flexibility is an important issue in improving qualification management (Johnzén et al. 2011). In this section, we first present flexibility definitions from the literature considering manufacturing level in Section 2.2.1 in order to understand and structure the base for the concept. Second, we expand our perspective to flexibility concept in SC level in Section 2.2.2. After combining all findings from the literature, a framework that is used in our simulation model is presented in Section 2.2.3.

2.2.2 Manufacturing Flexibility

Importance of manufacturing flexibility arises for companies in a challenging environment by many influencing dynamics and uncertainty, with objectives such as minimizing production lead-time or improving utilization in a job-shop level (Rowshannahad et al. 2015). Browne et al. (1984) introduce eight significant flexibility definitions to diminish ambiguities and clarify flexibility concept in manufacturing level, and they use these definitions to evaluate Flexible Manufacturing Systems (FMS). These eight definitions include machine, process, product, routing, volume, expansion, operation, and production flexibility, respectively. Later, Sethi and Sethi (1990) extend the structure presented by Browne et al. (1984) by adding three more definitions. These definitions are: material handling, program, and market flexibilities. They are to be considered in flexible transfer lines, assembly operations, and eventually in FMSs. The semiconductor industry needs higher investments for the tools in their wafer fabs when compared to other industries (Johnzén et al. 2011; Rowshannahad 2015). For this reason, it is crucial to use the tools at the most efficient level, and balance bottlenecks as much as possible. Additionally, product demand variability is remarkably high in wafer fabs with high downtime rate of tools. Thus, wafer fab management plays an important leading role. With all these definitions and information, Johnzén et al. (2011) emphasize the lack of mathematical definition for measuring flexibilities in the literature for balancing the workload in semiconductor fabs. Thus, their study includes three types of main flexibility measures. These measures are: toolset flexibility, WIP flexibility and the combination of both, the system flexibility measure. Being on a fab level, these are important definitions, however, as our objective in this study is on the SC level, we look beyond the fab level.

2.2.3 Supply Chain Flexibility

The flexibility of a SC is measured in the ability of the SC as whole to respond to changes and challenges such as demand volatility, disruptions due to natural disasters, and achieve efficiency through the optimization of the entire SC, not only through a single or through few participants of the SC (Rabe et al. 2012). According to Tan (2001), the flexibility in SCM is implemented for minimizing the unit product cost. This is the traditional practice in this field. The scope of this paper extends towards the ecological cost and impact of flexibility; that is, how the flexibility could reduce the carbon footprint of the company. According to Browne et al. (1984), establishing flexibility involves high cost due to the installation cost of sophisticated machines and the cost of highly skilled workers. However, establishing flexibility has the advantages of minimized unit cost, agility for coping with changes such as volatility of customer demand, and efficient production.

2.2.4 Flexibility Framework in Semiconductor SC

While it is possible to have more than fifty definitions at the manufacturing level only (Sethi and Sethi 1990), it is probable that the same applies to the SC level. Rabe et al. (2012) provide an invaluable resource and divide flexibility concept into five categories with different aspects with regard to the literature for SC flexibility. These categories include functional perspectives, dimensions, time horizon, hierarchical aspects, and influential factors. Referring to their work, a framework for semiconductor SC is created and a simulation model is determined. Our simulation model concerns CO_2 emission per component as an output at various levels of flexibility.

The ecological cost of flexibility consists of cost resulting from the built flexibility and used flexibility. The built flexibility concerns turning a percentage of the total capacity into a flexible share of capacity that is available to accept production requests. The used flexibility is the flexibility that is used after being built. The reason why not all the built flexibility can be used comes from the required demand. Assuming that 30% of flexibility is built but only 20% is needed, then 10% of built flexibility remains unused. Certainly, the ideal situation would be to use as much as possible of the built flexibility.

In terms of ecological cost, there is a share of emission related to transforming the percentage of the total capacity into a flexible capacity, this cost is referred to as the built flexibility emission and built flexibility cost. On the other hand, there is a share of emission related to using the built flexibility, called the used flexibility emission and used flexibility cost. The net flexibility emission is obtained by subtracting the used flexibility emission or the cost from the built flexibility emission or the cost. The built, used and net flexibility are described in formulas in Section 3.3. Figure 2 visualizes the related literature and its authors. Accordingly, this study stands at the intersection of flexibility, GSCM and semiconductor SC literatures.

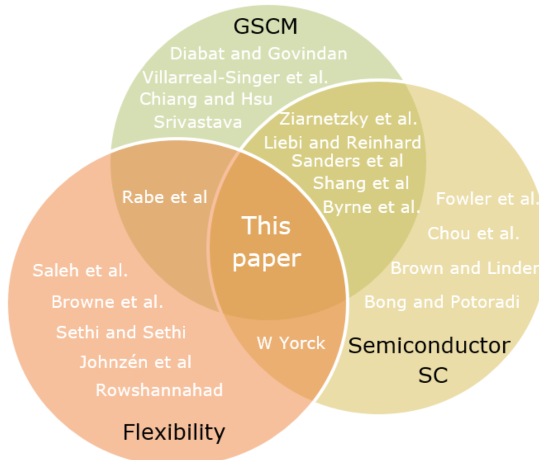


Figure 2: Overview of related literature.

3 METHODOLOGY

This section presents the SC simulation model and its conceptual model in Section 3.1 and the model calculations in Section 3.2.

3.1 SC Simulation and Conceptual Model

Simulation is a way to find solutions for complex problems of real-world systems (Grigoryev 2016). In this study, AnyLogic Software is used to conduct the experiments of the discrete-event simulation. The model is built based on the details from the original system in order to mimic the real-life phenomenon. After building the model, it is run for 441 times and analyzed to find the optimal solution. Figure 3 shows the layout of the modeled SC in this study with two front-end fabs, two back-end fabs and one distribution center (DC).

The aggregations and assumptions used to simplify the real-world system can be classified into product, production process and customer assumptions. The product line is assumed to be flexible in the sense that it can be produced at any wafer fab within the global SC, this excludes the technical restrictions of manufacturing the products at different sites. The process time is considered constant for all products and all plants, each product consumes one unit of capacity of the plant to be produced, while cycle time is assumed to be constant.

With regard to the production process, a pure pull system is considered. This allows to focus on the overutilization and underutilization of production capacities that result from the demand volatility due to the disturbance caused by the low forecast accuracy. The production process starts before the arrival of customer demand based on forecasted demand. Therefore, stock levels are not included in the scope of this paper. The modeled system is assumed to have a certain level of forecast accuracy, average capacity utilization and flexibility. The capacity levels at each production site is considered constant for the specific process. Also, it is assumed that the production process is not restricted to a geographically fixed location. However, the entire SC can be considered as one global production plant. Additionally, no location preferences concerning cost and quality are included.

The ecological cost of the production process is assumed to result mainly from electricity, because of its high share of the total emission. That is, electricity accounts for 51% of the total emission -an example is the Annual Report 2017 of a semiconductor company (Infineon Technologies AG 2017) as in Figure 5. This assumption does not mean that the electricity is the only source of emission in production. The cost is divided into fixed and variable emissions. The fixed emission is the emission to maintain cleanroom conditions. It is output-independent, while variable emission is to produce components, and it is output-dependent. In front-end fab, the fixed emission is considered to account for 60% of the total share of emission, while the variable emission accounts for 40% of the total share of emission. In back-end fab, the fixed emission and variable emission account for 60% and 40%, respectively.

With regard to the customer order assumptions, performance indicators such as service level or other relevant indicators are not considered in the scope of this paper. Therefore, as a simplification, all the finished products moved to the distribution center from the back-end fab are directly moved to the customer.

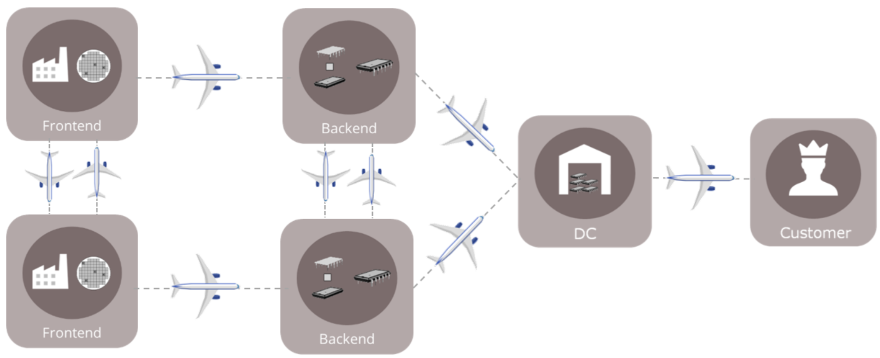


Figure 3: The layout of the modeled SC.

3.2 Model Calculations:

The model calculates the emission for one component resulting from the production, the flexibility and the transportation. The orders are modeled stochastically to indicate the influence of the forecast accuracy on the ecological impact. In the model, the ecological impact is formulated as a function of three parameters, namely F/C, Flex, and U.

Where F/C is the forecast accuracy (%), Flex is the flexibility (%) and U is the average capacity utilization (%). The F/C is defined in this paper as the demand fluctuation yielding to varying capacity utilization around the U. The flexibility in this model is considered as the share of the total capacity available for flexible production measured in percentage of total capacity, the flexibility is divided into built flexibility and used flexibility. In this simulation model, the built flexibility is the parameter used to describe the share of the total capacity that is available for the flexible production, while the used flexibility is accounted for in the ecological cost calculations. The model time unit is weeks, while the components are aggregated into batches.

For the sake of simplicity, a simple model to calculate the variable emission and the variable cost is used. This is shown in Figure 4. Therefore, the ecological cost of the production for each plant is calculated as follow:

$$Plant\ Emission = Fixed\ Emission + \left(Variable\ Emission * Output\right)$$

where the plant emission and fixed emission are measured in ton of CO_2 per week, the variable emission is measured in ton of CO_2 per batch and the output is measured in batch per week. In addition, the economic cost of production in euro per week for each fab is calculated as follow:

$$Plant\ \text{Cost} = Fixed\ \text{Cost} + \left(Variable\ \text{Cost} * Output\right)$$

where the plant cost and the fixed cost are measured in euro per week, the variable cost is measured in euro per batch and the output is in batch per week. The plant emission and plant cost for the two frontend fabs and the two backend fabs are calculated and added to obtain the total plant emission. While, transportation emission is calculated as in the following:

$$Transport\ Emission = Dis\text{tance} * \left(EF * Weight * Shipped\ Products\right)$$

where the transport emission is measured in ton of CO_2 per week, the distance is in kilometers, the EF represents the emission factor which is given in ton of CO_2 per kilogram of shipped products per distance travelled, the weight is measured in kilograms per batch and the shipped products are measured in batch per week.

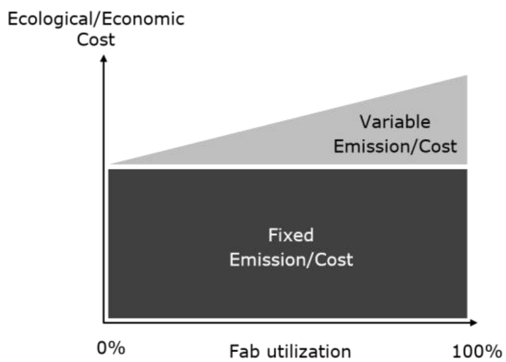


Figure 4: Fixed and variable emission per cost of production with fab utilization.

The flexibility emission, measured in ton of CO2 per week, is divided into built flexibility emission, the used flexibility emission and the net flexibility emission. They are calculated in the model as in the following:

$$Built\ Flexibility\ Emission = \left(Variable\ Emission * Capacity * Flexibility\right)$$

$$Used\ Flexibility\ Emission = \left(Variable\ Emission * Flexible\ Load\ Produced\right)$$

$$Net\ Flexibility\ Emission = Built\ Flexibility\ Emission - Used\ Flexibility\ Emission$$

$$Total\ Emission = Total\ Plant\ Emission + Transport\ Emission + Net\ Flexibility\ Emission$$

Where the output is the number of components produced per week and the flexible load is the number of components produced flexibly per week. The key performance indicators (KPIs) used in this paper are the unit ecological cost (expressed in gram of CO_2 per component), it is calculated as:

$$Ecological\ \text{Cost} = \left(\frac{Total\ Emission}{Total\ Output}\right) * Unit\ Convertion$$

Similarly, the unit economic cost (expressed in euro per component) is calculated by:

$$\text{Economic Cost} = \left(\frac{\textit{Total } \text{Cost}}{\textit{Total Output}} \right) * \textit{Unit Convertion}$$

where the total output is the total number of components arrived to the DC per week. The unit conversion is used to convert the tCO_2 per batch to gCO_2 per component.

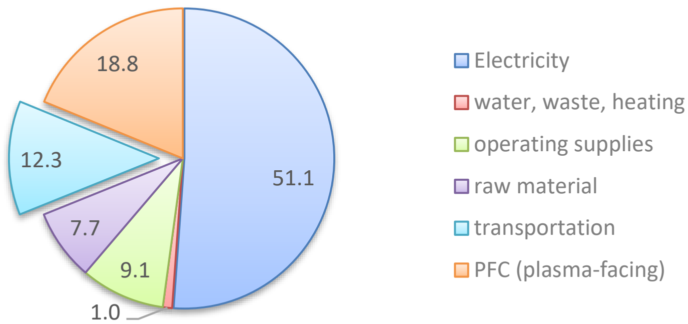


Figure 5: Total emission per source (Sustainability at Infineon Report FY 2017).

4 RESULTS

The analysis of results is based on a parameter variation experiment in which the aim is to study the interdependences of three parameters, i.e., Flex, F/C, and U on the model KPIs. The analysis shows the extent to which the optimization of each parameter can contribute to the reduction of the unit ecological and economic costs. In order to understand which parameters or set of parameters have the optimal value of the KPI, the value of the KPI of each parameter is investigated by performing 441 runs of the simulation model along the whole range of each parameter. Each parameter is analyzed within a range from 0% to 100%, with a step of five percent, while keeping the values of other parameters constant. The measurement period and delay describe how long the model is run until a value is registered. This allows simulating the SC with the same set of parameters for a longer time to ensure high quality results. Figure 6 shows the analysis part of the model. The model is built to allow a user-friendly GUI in which users can edit the input data of the simulation. The above analysis is performed for all values of flexibility under a particular value of F/C that the model user can input to the model. This allows to know the percentage of flexibility that gives the lowest value of the unit ecological cost for the given F/C entered by the model user.

The analysis shows that the best value of the KPIs occurs at a flexibility of 0% for a value of F/C of 100%. This explains if the customer demand is adequately forecasted, there is no need for flexibility. This scenario is the idealistic situation. It is noticed, also, that the flexibility emission increases with the increase of flexibility percentage, and that the used flexibility cost is zero. The transportation emission remains constant because of the simplified assumptions.

The optimal value of the KPIs at a F/C of 80% is at 10% flexibility. The drop in the unit ecological cost at a flexibility of 10% is due to the increase in the total output and the optimization of the plant emission. The transportation emission increases because of the flexible transportation between the different locations. However, this does not affect the trend of the KPIs due to the minor influence of the emissions from transportation. The same results are obtained for the unit cost in Euros since it is obtained based on the same assumptions. Figure 7 shows the situation of the SC at a value of F/C of 80%. This result means that it is necessary to have a level of flexibility of 10% in the global SC in order for the SC to be able to cope with the demand volatility. For the value of F/C of 50% (see Figure 8), which means that there is a 50% deviation from the true customer demand. This is quite similar to the situation in the semiconductor industry due to the bullwhip effect. The results show that the lowest value of CO_2 per component is obtained at a flexibility of around 22%. This means that the SC would have to enable a flexibility of around 22% to cope with the demand volatility. The drop in the CO_2 per component occurred due to the increase in the total output. The increase in transportation emission is negligible compared to the decrease or the optimization of the electricity emission.

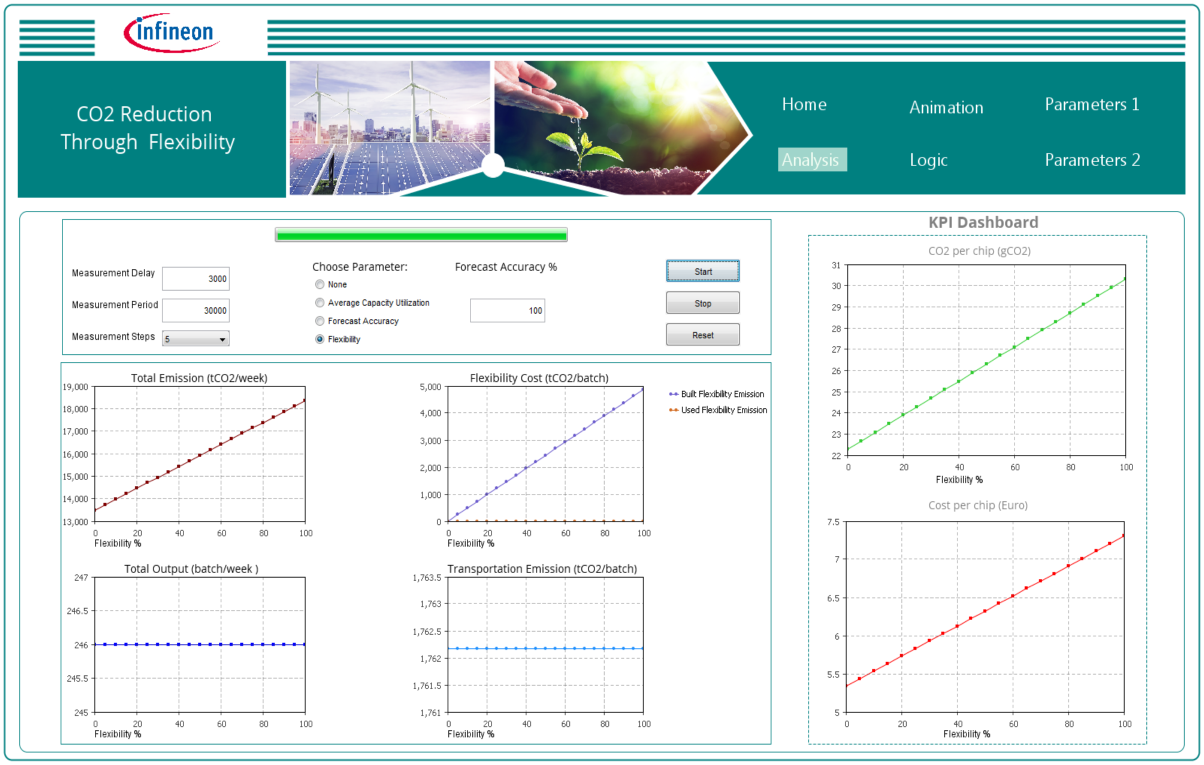
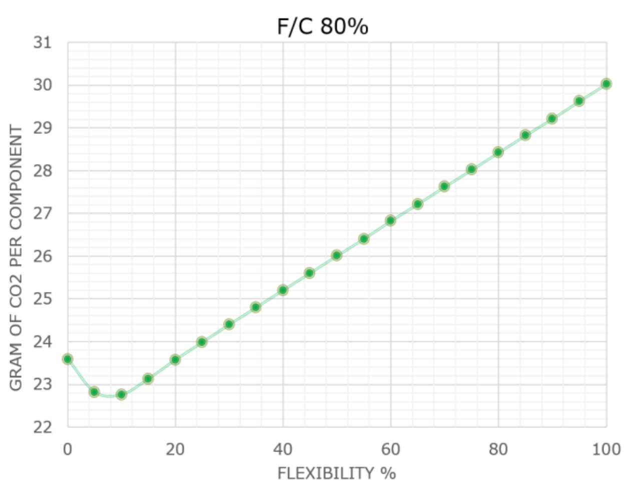


Figure 6: Model analysis GUI and results for F/C of 100%.



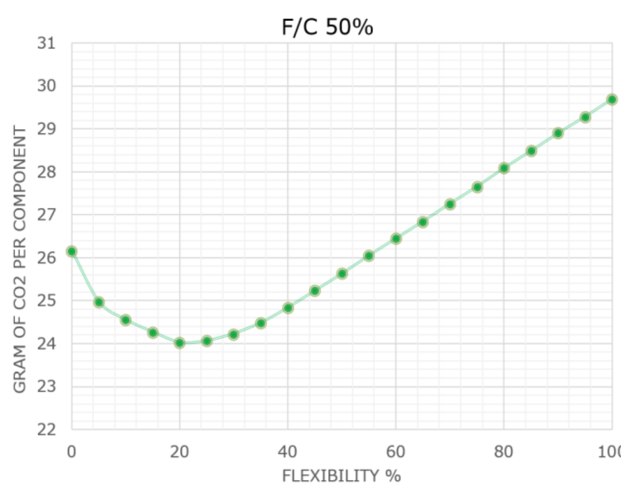


Figure 7: Model Results at F/C 80%.

Figure 8: Model Results at F/C 50%.

To give a clearer picture of the parameters variation, the KPIs are analyzed for all the values of the F/C and flexibility, this gives a 3D graph, in which the X-axis and Y-axis are the flexibility and F/C, respectively, while in the Z-axis the CO_2 per component as in Figure 9. Based on expert knowledge, the typical situation of the KPIs in the semiconductor industry can be plotted on the 3D Surface, this graph represents the set of the possible solutions of the optimization problem. The model shows that the best value of CO_2 per component are obtained for high value of F/C, and as the F/C decreases, the best values are obtained when a certain degree of flexibility is enabled in the global SC.

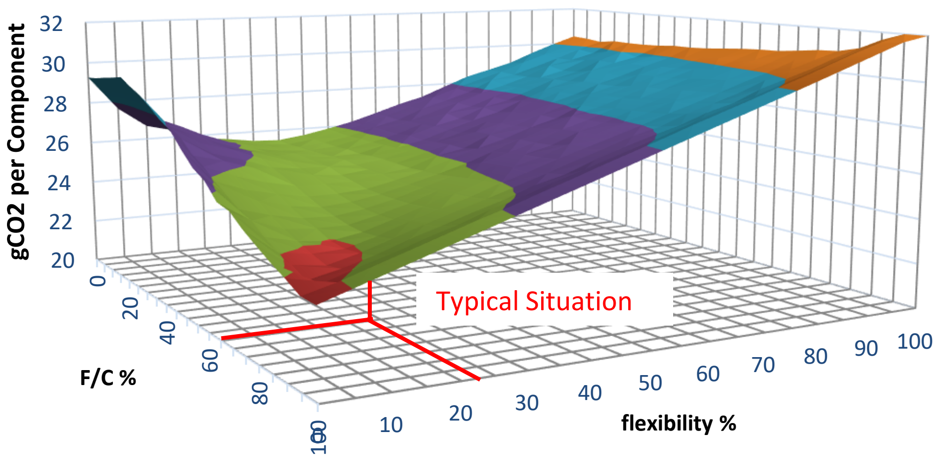


Figure 9: Model Results plotted in a 3D Graph.

5 CONCLUSION AND OUTLOOK

The main goal of this work was to investigate the impact of flexibility in a global semiconductor SC, enabled by a global network of transportation, on the carbon footprint of the products as well as overall economic cost per product. The paper emphasizes a potential situation and shows that under the assumptions of having high CO_2 burden in manufacturing, low in transportation and high demand volatility, flexibility in a global SC is an enabler for both CO_2 and cost reduction through optimizing the production capacities of the SC, and leveraging the global network of transportation. The model indicates the correctness of this starting hypothesis. The positive impact of that is due to the optimization of the electricity emission, which accounts for the most significant share of total emissions, while the increase in the transportation emission is of low influence on the CO_2 cost per chip, along with economic cost per chip.

The model states that electricity emission is by far the major driver in the semiconductor industry due to the need for cleanroom conditions as a prerequisite for manufacturing. These emissions are fairly independent of the level of utilization. This explains why at lower forecast accuracy and absence of flexibility the CO_2 per component is high. The results of the model show the best values of the KPIs obtained for different values of flexibility. The optimal value of CO_2 per component is obtained at higher forecast accuracy values. The lower the forecast accuracy, the more flexibility is needed to enable the SC to cope with the demand volatility. This gives space for maneuvering for companies to choose the value of flexibility that gives the best carbon footprint. Also, this paper demonstrates that the forecast accuracy, the flexibility and the average capacity utilization are the key parameters for the ecological impact evaluation.

The simulation model in this paper uses a pure pull system to describe the behavior of the SC. However, the situation needs to be studied from a push-pull system, which is the system used in reality. This implies adding inventory and stocks to the SC, which makes the model more realistic.

For simplification, the model assumes one product line with a constant level of demand volatility. However, the most significant ecological influence of flexibility on the sustainability of a SC is very clear for products, which are typically very volatile. These products make fabs reach capacity limits during an economic upturn. Such products should therefore have more flexible capacities than products with a more stable demand. Therefore, it is recommended that the model is extended to include more product types with a stable demand and others that have volatile demand.

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