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ENERGY-EFFICIENT SEMICONDUCTOR MANUFACTURING: ESTABLISHING AN ECOLOGICAL OPERATING CURVE

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ABSTRACT

Latest governmental policies aim to mitigate the carbon impact on climate and accelerate the transition towards carbon neutrality by imposing stronger regulations for companies. The semiconductor industry emits carbon dioxide caused by its large amounts of consumed energy. At the same time, machine sensors tracking consumption are rare, and the share of fixed and variable energy consumption is often unknown. To detect the individual energy consumption types of a wafer fab, a process- and infrastructure-oriented discrete-event simulation model is developed that serves as a tool to determine the plant energy consumption within a fab. The obtained shares are validated with existing data. In parallel, a novel enery efficiency curve is constructed and verified by extending the concept of the well-studied Operating Curve. It incorporates the relationship between utilization and energy efficiency and adds an ecological viewpoint to the so far only economically motivated concept.

1 INTRODUCTION

In the face of the Covid-19 pandemic, global policymakers seek to mitigate the impact of climate change after 2030 by striving towards decarbonization and thereby limiting global warming to 2 ˚C above pre-industrial levels (KPMG 2020). Sustainability is consequently no longer a nice-to-have for worldwide companies but will be an obligation in the near future due to emerging standards and regulations (Paul et al. 2020; Schneider et al. 2022). The European Green Deal by the European Commission (2022) has set the guidelines for Europe to become the first carbon-neutral continent by 2050. Exact regulations on the EU level in the Corporate Sustainability Reporting Directive exist as a proposal to date, and companies should plan to apply them for 2023 retrospectively (European Commission 2021). In terms of ecological improvements energy efficiency gets especially into the spotlight since 75 % of the greenhouse gases in Europe result from the generation or usage of energy (European Commission 2022). A general understanding of energy efficiency in literature is the ratio between the output of a manufacturing system, such as parts, weight, or economic value, and the delivered input to it, for instance, electricity, gas, or oil (Thiede 2012; Omar et al. 2016; Diaz and Ocampo-Martinez 2019).

Suppliers of semiconductors show comparatively high energy intensity in production. They thus represent a group heavily under pressure to increase the energy efficiency as a major milestone towards ecological sustainability. Three general steps are necessary to manufacture semiconductors from their substrate silicon: the production of raw wafers, the so-called frontend production, and the backend production (Mönch et al. 2011). The high amounts of consumed energy in the semiconductor industry originate mainly from special environmental conditions required within the frontend production, the wafer fabrication (Hu et al. 2020). Such cleanroom conditions imply, among others, a specific level of

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temperature, air pressure, humidity, and cleanliness (Ma et al. 2021). Frontend locations consume the largest amount due to the highly demanding and stable climatic conditions in the cleanrooms (Gopalakrishnan et al. 2010). Cleanrooms, in general, consume up to 50 times more energy than typical commercial buildings. Depending on the production conditions, they require more than a hundred air changes per hour enabled by techniques such as high-efficiency particulate air and ultra-low particulate air (Kircher et al. 2010). In addition to those infrastructural installations delivering the cleanroom conditions, individual production machines represent a further type of energy consumption and is related to the actual production. The urge to increase energy efficiency with appropriate energy-saving activities is thus apparent. To appropriately tailor such actions, the individual energy consumption of semiconductors requires a sufficient level of transparency which is a considerable challenge for fabs that lack individual machine sensors (Diaz and Ocampo-Martinez 2019). Companies find themselves confronted with energy consumption data on a building level only, which is far from drawing any possible conclusions regarding the impact of production volumes on energy consumption. This lack raises the interest in concepts that add visibility to a more granular energy consumption level.

This paper aims to develop an extension to the existing Operating Curve (OC) concept (Aurand and Miller 1997) by investigating the effect of utilization on energy efficiency. It uses the results of discrete-event simulation (DES) on a fab level to verify the novel concept. The structure of this paper is organized as follows: Section 2 provides an overview of existing literature in the field of energy efficiency-related simulations and latest contributions to the original OC concept. It is followed by the conceptual construction of a novel Operating Curve in section 3. Subsequently, the simulation model will be proposed in section 4. Results will be discussed in section 5, and the paper concludes with an outlook in section 6.

2 LITERATURE REVIEW AND RESEARCH BACKGROUND

This section summarizes the existing approaches in the two relevant fields of literature: Energy efficiency-related simulation methods to analyze the ecological operating performance of a fab, which are extended by the second field of literature regarding the established OC concept.

2.1 Simulation of Energy-efficient Systems

Energy efficiency has received special attention from recent simulations. Several contributions consider the actual energy consumption, while others do not specifically model the consumption but incorporate efficiency in the final result analysis after deriving simulation results. In addition, rather detailed approaches deal with the energy consumption of production-independent equipment and the manufacturing itself. Finally, DES or Petri-net modeling are perceived to be promising approaches to model sequential process flows while focusing on energy awareness. Yoon and Chae (2019) interpreted sustainability as a matter of production performance and overall production efficiency, which then also leads, among others, to energy consumption reduction. With the obtained simulation results, they analyze the efficiency of several scheduling policies for the required jobs in the specific semiconductor process of consideration. Seow and Rahimifard (2011), Thiede (2012), Omar et al. (2016), and He et al. (2022) tracked the actual energy consumption throughout the simulation process. Their approach is to calculate the energy consumption based on the flow of products throughout a sequential path. He et al. (2022) additionally showed that the energy consumption of machines could be reduced by flexible machine sequences and tool paths. Another method integrating energy efficiency in simulation frameworks is the detailed energy analysis or optimization of the obtained results; Jeon and Prabhu (2013) proposed an energy-aware model based on queuing theory that considers re-entrant flows in the semiconductor manufacturing processes. The model investigates the energy reductions achieved by running tools at a lower power state when idling. Latorre-Biel et al. (2018) presented an approach with a simulation in which products obtain services from several machines. The approach helps in developing environmentally friendly strategies. Guo et al. (2021) introduced a method for creating a digital twin of an air conditioner production to simulate and optimize the smoothening of the production line in a flexible cellular manufacturing environment. Efficiency measures can be derived from the subsequently formulated multi-objective optimization. In contrast to this paper, they do not consider the relationship between production quantity and energy consumption. Thiede (2012) stated that most of the obstacles in the literature regarding a detailed simulation of manufacturing processes and their respective energy consumption are based on the complex interdependencies within manufacturing and related systems. Therefore, they presented several models which reflect mass production with continuous material flow. They reflect system interaction with so-called technical building services that enable the required manufacturing environment and therefore are additional energy consumers. In addition to that, Seow and Rahimifard (2011) deal with interactions between production and production-independent equipment. They established an approach to investigate the energy efficiency in a top-down approach from the plant and process level until the product design itself. Their plant level model differentiates between direct and indirect energy consumption. Omar et al. (2016) extended the stream of literature with a hybrid simulation model. The energy is consumed at a process and plant level, and the hybrid character of the modeling approach results from the synchronization of the discrete manufacturing with a real-timeframe, adding the continuous component. Seow and Rahimifard (2011), Thiede (2012), and Omar et al. (2016) realize the simulation task with the DES technique. Developed with the same tool, the digital twin of Resman et al. (2021) additionally includes a five-step approach breaking down a smart factory into building blocks with their respective processes. An appropriate selection of parameters allows for later control of the real manufacturing system and its performance. Another modeling technique is applied by He et al. (2022), and Latorre-Biel et al. (2018) which use an objected-oriented Petri-net to connect the discrete points of a production system. Gopalakrishnan et al. (2010) developed a computer-based interactive model which estimates the energy consumption for specific energy intensive processes. In a second step they conducted senstitivity analyses on energy consumption with several production variables. Kircher et al. (2010) investigated general cleanroom energy efficiency charactersitics regardless of production with a transient system simulation software. They proposed energetic approaches such as reheating or solar preheating to reduce energy consumption in production. A detailed summary of the latest approaches increasing energy efficiency is given by Diaz and Ocampo-Martinez (2019).

In contrast to the majority of contributions, this paper focuses on the perspective of an entire plant. Therefore, it includes its arrangements of processes and all supporting infrastructural installations that support both the process line and the required manufacturing environment. To the authors' knowledge, no contribution has been published in this field in combination with the complex manufacturing characteristics of the semiconductor industry.

2.2 The Operating Curve

The semiconductor industry is severely challenged simultaneously by two competing goals, the need for a quick delivery of products to the market and the strive for high utilization rates of costly equipment. Therefore, respective performance measurements to achieve those targets are based on insights from queuing theory. They predominantly rely on the (M/M/1) queuing system, consisting of interarrival rates of orders and processing rates of machines. Both rates are exponentially distributed, and one service station is available. One of the essential takeaways from queuing theory is that the cycle time (CT) grows exponentially with increased utilization. Hence, the CT is denoted as the sum of all queuing (QT) and raw process times (RPT) of a line ($CT = QT + RPT$), while the RPT is defined as the theoretical minimum amount of time that one lot requires to get processed from the start to the end of a line (Hopp and Spearman 2011). To tackle the trade-off between high utilization and small CT, the original concept of the OC, also known as the characteristic curve, was elaborated. It provides a widely-used toolset for considering a semiconductor fab's production performance at a given operating state α (Aurand and Miller 1997). It can be seen from the curve that the CT and thus the Flow Factor (FF), $FF = CT/RPT$, becomes much more sensitive as the utilization rate approaches hundred percent. This relationship is determined by the equation of Kingman (1961), which approximates the mean queuing time in a (M/M/1) system and, which can be applied for single as well as multi-machine stations (Hopp and Spearman 2011). The approximation of the queuing time is accordingly described by (1). c_{RPT} and c_{IA} are variation coefficients of the raw processing time and interarrival time, obtained by consideration of their standard deviations. $U = RPT/IA$, refers to the fab utilization as the ratio of the RPT to the interarrival time (IA). The first factor of (1) represents a fab characteristic constant value and is often referred to as the variability of a system, also known as alpha (α) (Ehm et al. 2011). A fab's CT can therefore be given by (2). With (2) and the introduced FF ratio, the equation for FF is provided by (3) as described by Winz et al. (1999).

$$QT = \left(\frac{{c_{RPT}}^2 + {c_{IA}}^2}{2}\right) * \left(\frac{U}{1-U}\right) * RPT \quad (1)$$

$$CT = \alpha * \left(\frac{U}{1-U}\right) * RPT + RPT \quad (2)$$

$$FF = \alpha * \frac{U}{1-U} + 1 \quad (3)$$

The constant value of the operating state, the variability α, depicted by one single OC, indicates, therefore, the level of maturity of a fab's manufacturing line. More specifically, the smaller the value of α is, the less likely a production line faces a disruption upon utilization increase that leads to a blown-up CT. Examples of variability and, therefore, harm to the production performance are, among others, machine failures, setups, and required rework (Hopp and Spearman 2011). An individual OC, therefore, depicts the performance of a fab for a previously chosen period and a given variability α. In this period, the factory can operate at one specific operating point on its current OC. So, given a fixed level of product and process maturity and the aim of increasing its utilization a fab would move up the OC to an operating point with higher utilization but also higher CT and FF. The contrary effect of a smaller CT and FF would occur if a fab had decided to reduce the utilization to a certain level (Aurand and Miller 1997). The optimal fab operation state is, therefore, a combination of utilization and CT that best balances the trade-off. The optimal point on the OC would be, accordingly, at the curve's "elbow". However, if the factory managed to reduce its variability due to production smoothening measures or predictive maintenance, the fab would shift the curve α_1 to the right and run its manufacturing at a reduced variability level α_2 depicted by the lower OC. The OCs α_1 and α_2 are also visualized in Figure 2.

Several extensions to the basic OC have been published in the last two decades. However, none of them addresses an ecological consideration. The first group of authors deals with methodological approaches on how to obtain OCs in general. Fowler et al. (2001) addressed the challenges of computational performance when generating an OC that captures changes in production details. They apply a simulation-based fixed-sample size method with sampling weights to increase the run-time. A promising alternative to a simulation-based OC that similarly saves time and resources is presented by Can et al. (2014). They constructed several semiconductor process OCs by applying a genetic algorithm that uses machine learning to create models which deliver specific values for CT and throughput. Nazzal et al. (2006) added an economic evaluation from an industry perspective to the field; their simulation serves as the baseline which is compared to several scenarios of capacity extensions on a process level. Weber and Fayed (2010) further specified the economic perspective. They created a hypothetical OC which is extended by a cumulative profit curve and incorporates economies of scale for wafer processing cost and total cost of ownership. With a fab simulation, they showed that the solely output-driven approach aiming for minimum CTs might recommend other capacity volumes compared to the approach which intends to maximize profit. Due to mainly cost-driven businesses, a fab's most critical challenge is to enable high utilization but low CTs. This can only be achieved by reducing fab variability, according to Ehm et al. (2011). They claimed that if variability cannot be avoided, it should be synchronized and stabilized by automated systems. This direction of synchronization is further elaborated by a stochastic simulation by Horn and Podgorski (2019). Their approach reduced the overall frontend variability, which is not only suffering from process variability but also amplified by the lack of a just-in-time linkage of subsequent processes of an automated material handling system. With a hybrid concept, the authors achieved an outstanding shift of the OC towards the right.

3 DEVELOPMENT OF THE ECOLOGICAL OPERATING CURVE

Considering a single fab and the OC concept led to the idea of deriving an analogous curve that incorporates the relationship between utilization and energy efficiency.

The original, only economically motivated OC represents a function of the FF ($FF = CT/RPT$). It considers a ratio of an "idealistic" time, the RPT, and a "realistic" time, the CT. In the semiconductor industry, the emissions per product are commonly used to create an ecological perspective on a manufacturing system's efficiency (Hamed et al. 2019). Analogously, this paper considers the energy consumption per product and defines a new "ideal" and "realistic" variable for a fab's energy consumption. Therefore, the following consideration is made: A fab would achieve an ideal energy consumption per chip ($E_{chip,ideal}$) if it were completely utilized by producing an output that equals its capacity C. In reality, the fab can only produce a realistic going rate (GR) and therefore has to accept a realistic energy consumption per chip ($E_{chip,real}$). For each scenario, the total energy E_{total} is therefore divided by the respective output, assuming that the entire energy consumption is hundred percent fixed. This assumption will be released later on. The two scenarios, consisting of one ideal and one real case for energy consumption per chip (analogous to RPT and CT), are therefore given by (4) and (5). In the next step, the ratio of the real to the ideal scenario is constructed with the role model of the existing FF. It will be called Ecological Factor (EF) and serves as an indicator for the ecological efficiency in addition to the economic efficiency, determined by the known FF. Assuming a hundred percent fixed energy consumption and that utilization can be also understood as the ratio of GR to the available capacity C, the following relationship for EF_{fix} can be derived and is provided by (6). This leads to the conclusion that EF_{fix} is completely independent of total emissions. Moreover, the energy efficiency is improved with utilization levels as large as possible to decrease the consumption per chip. In other words, the EF indicates how much excess energy is generated due to a not completely utilized fab.

$$RPT \triangleq \frac{E_{total}}{C} = E_{chip,ideal} \tag{4}$$

$$CT \triangleq \frac{E_{total}}{GR} = E_{chip,real} \tag{5}$$

$$EF_{fix} = \frac{E_{chip,real}}{E_{chip,ideal}} = \frac{\frac{E_{total}}{GR}}{\frac{E_{total}}{C}} = \frac{C}{GR} = \frac{1}{U} \tag{6}$$

The assumption of an entirely fixed energy consumption will now be released. A typical energy consumption pattern in semiconductor manufacturing can be explained by two variables: First, the continuously maintained cleanroom conditions regardless of the production volume cause a macroscopically constant energy consumption. They generate the predominant share of energy consumption in the semiconductor industry (Kircher et al. 2010). Second, the fluctuating production volume additionally causes a variable energy consumption. The characteristics of this relationship can be assumed as linear based on the observations presented in Gopalakrishnan et al. (2010). For the following concept, thus, a fixed base of fixed energy consumption is always accounted for regardless of the utilization level. Depending on the utilization level, the variable energy consumption is added to the fixed energy consumption of the fab. As stated above, a linear relationship between the utilization and the variable energy consumption is assumed. Therefore, one can conclude that the higher the utilization is, the higher the total variable consumption and thus the total fab consumption. This development is visualized in Figure 1 and applies the total-maximum energy consumption ratio, E_{ratio} [%] $= E_{total}/E_{max}$. E_{total} is the sum of fixed and variable energy consumption for a given utilization level, while E_{max} refers to the theoretically maximum energy consumption at a hundred percent utilization. E_{ratio}, therefore, indicates how much of the current total energy consumption is generated compared to the theoretically possible energy consumption. At the boundary case of zero percent utilization, no variable energy consumption is generated. Therefore, the fixed energy consumption equals the total energy consumption. The so far unknown share of fixed energy consumption (later called α_e) on total energy consumption at full utilization can thus be retrieved.

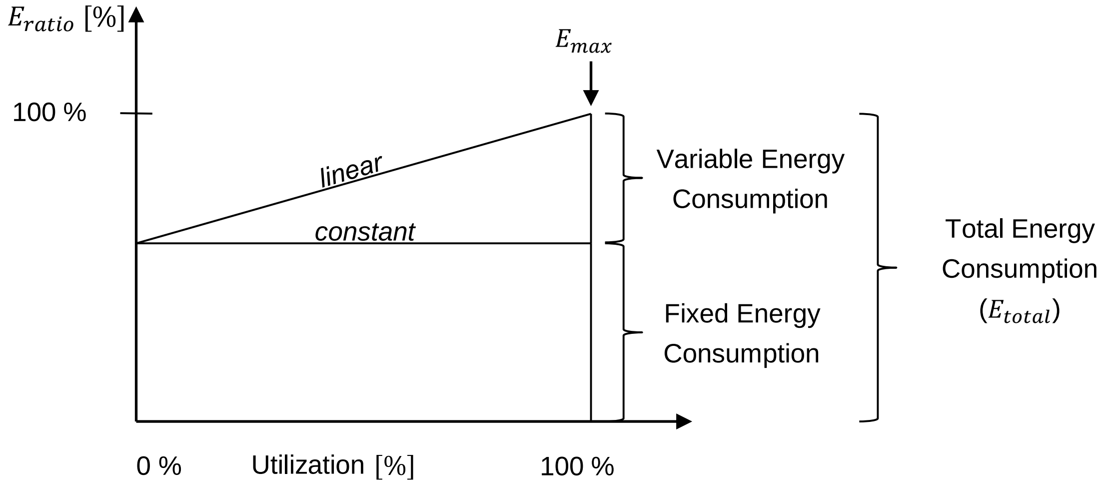

Figure 1: Concept of fixed and variable energy consumption in relation to maximum energy consumption.

With this concept in mind, the maximum possible energy consumption E_{max} can be used to construct an EF that captures both types of energy consumption (7): The previously used E_{total} is split into a sum of fixed energy consumption and the utilization-dependent variable energy consumption. Both parts of the total energy consumption are described with the share of fixed energy consumption α_e. Assuming that $U = GR/C$, and reducing the fraction by E_{max} returns equation (8). EF is thus only dependent on the utilization variable U (11) and can be added into the existing concept of the original OC with the yet-existing FF. Comparable to the original FF, the EF is dimensionless and is defined for values larger and equal than one (9). An EF equal to one would mean that a fab is ideally splitting its energy consumption along with its throughput at a utilization of one hundred percent. The fixed share of energy consumption α_e (10) is accordingly understood as a coefficient that amplifies the impact of utilization on energy consumption. Consequently, it defines the degree of impact the current utilization level has on a fab's energy consumption. The conceptual idea as an integration into the existing economic concept is visualized in Figure 2. The new curve will be called Ecological Operating Curve (eOC); all extensions are indicated by the index e.

$$EF = \frac{\alpha_e * E_{max} + (1 - \alpha_e) * E_{max} * U}{GR} * \frac{C}{E_{max}} \tag{7}$$

$$EF = \frac{\alpha_e}{U} - \alpha_e + 1 \tag{8}$$

$$EF \geq 1 \tag{9}$$

$$0 \leq \alpha_e \leq 1 \tag{10}$$

$$0 \leq U \leq 1 \tag{11}$$

Similar to the original concept, the fab can run only at one ecological operating point at a time. If a fab increases its utilization, it will move down the ecological OC, e.g. α_{e1}, to a lower value of the EF and would therefore increase its energy efficiency per product. If a fab even achieves a structural change of its energy consumption by a reduction of the fixed energy consumption share, it could run at a lower eOC, located at the left part of the graph, e.g. α_{e2}.

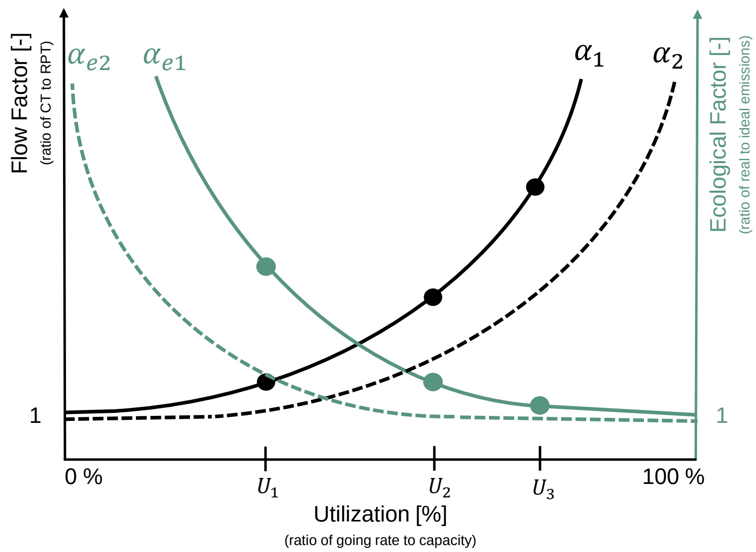

Figure 2: Economic and Ecological Operating Curves.

The plot in Figure 3 illustrates the behavior of the EF. The EF is plotted along the spectrum of utilization for several curves of which each represents a fab's individual parameter of fixed energy consumption shares α_e. The last curve in the back with α_e = 1 shows the largest gradient compared to the curves in the front. It means that the reduction impact of utilization on energy consumption per chip is the highest for hundred percent fixed energy consumption. For the sake of clarification, the initial ratio of $EF = E_{real}/E_{ideal}$ is considered again in a scenario comparison on chip level. One can conclude that if α_e is as small as possible (close to zero) indicated by the OCs in the left part of the plot, the current utilization level has the least impact on improving the energy efficiency per chip. The total energy consumption in those cases is only variable energy consumption divided by the production volume. The energy consumption per product stays the same, regardless of utilization. For an α_e as large as possible (close to one), the scenario would approach the initially considered case with a hundred percent share of fixed energy consumption. In this case, an increase in utilization would have the maximum possible reduction effect of energy consumption per chip. Similarly, to the original concept, this ecological extension can serve as a tool for production management and control since it is not only applicable to an overall fab but can also analyze the ecological optimum for single processes. It would hence require information about process individual utilization, CT, RPT, and energy consumption. The latter is already provided by the simulation output of the later introduced model (see section 4). Consequently, a semiconductor company could compare two processes also in terms of product energy-efficiency when discussing new production strategies. Consider two given processes p and j with the same variability α and failure rates higher than other processes in the fab. Process p consumes more energy than j, and j is the production bottleneck. Furthermore, assume that process p has a larger fixed energy consumption share α_e than process j due stronger air and temperature requirements. While the fab's operations management in the past only might have focused on production smoothening of j to reduce the FF of the total fab it might now direct its attention also towards p. With an improved variability of p, the fab could utilize p by a larger rate and thus achieve a better product energy-efficiency of the fab while CT and thus production performance stays the same. The first and originally prioritized bottleneck j

would further contribute to reduce the company's energy consumption per product. This provides an example that ecological and economic objectives can benefit each other.

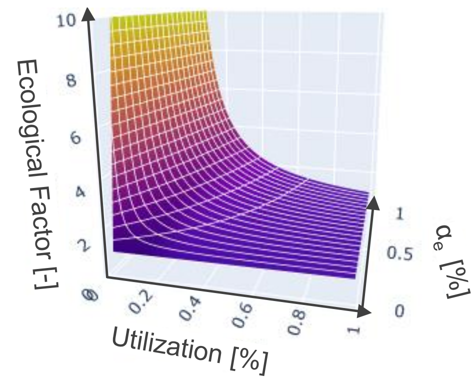

Figure 3: Range of EF for a possible spectrum of eOCs.

4 METHODOLOGY

A fab-oriented simulation with consideration of the individual energy consumption is presented in the following. It serves as a verification tool for the proposed theoretical concept extension by the eOC and provides a solution to determine unknown process-individual energy consumption shares. This section, therefore, introduces the methodological approach for constructing the simulation model and its energy-flow setup.

4.1 Simulation Approach

Modern simulation modeling as a tool to create a less complex model of the real world can use different techniques: DES is one of them and operates at a low or medium-low abstraction level with the goal of simulating a production process, for instance. Model entities are moving through a sequence of blocks where they are processed, delayed, seized, or released (Grigoryev 2018). Since the proposed model is based on a sequential flow network of several production processes, DES was chosen as an appropriate simulation technique. The model development follows the guidelines for a simulation study by Banks et al. (2005). The simulation was created, verified, and validated using the simulation software AnyLogic 8.

4.2 Simulation Setup and Energy Flow Network

The procedure for the simulation encompassed the construction of a model that represents data obtained from a typical semiconductor fab in the northern hemisphere. The processes were selected with reference to Mönch et al. (2011) for general relevance and Gopalakrishnan et al. (2010) for their criticality in terms of energy consumption. Besides that, previously generated qualified synthetic data was added as a data input to the model. The simulated energy consumption flow is constructed as a top-down approach to derive unknown consumptions and their respective shares with parameter calibration. In detail, total energy consumption obtained as historic data is narrowed down into individual consumption types of infrastructure installations and processes. The parameters break down the energy consumption into several types. The sum of those types thus replicates the original input of total energy consumption. After successful calibration, they serve as estimators for the yet unknown granular values of process individual energy consumption as was recommended by Omar et al. (2016). The proposed simulation model considers the infrastructure energy consumption to be constantly fixed, while the production processes also possess a share of variable energy consumption in addition to their fixed energy consumption. The energy flows modeled throughout the process and infrastructure types are monitored and deliver a digital twin of the original energy consumption. This served as control tool for the parameter calibration of the individual consumption types and their shares. For the calibration, 500 replications with a run length of 70 periods were carried out. The two energy flows considered by the model are visualized in Figure 4. The first is a sequential flow of four selected frontend processes $P = 1, \dots, j$. One generic product is manufactured throughout the sequence with a simplified re-entrant flow repeating the respective processes by an indicated number of loops. The numerous repetitions of production steps are typical for frontend manufacturing. The number of loops N can be accordingly altered to the selected product characteristics.

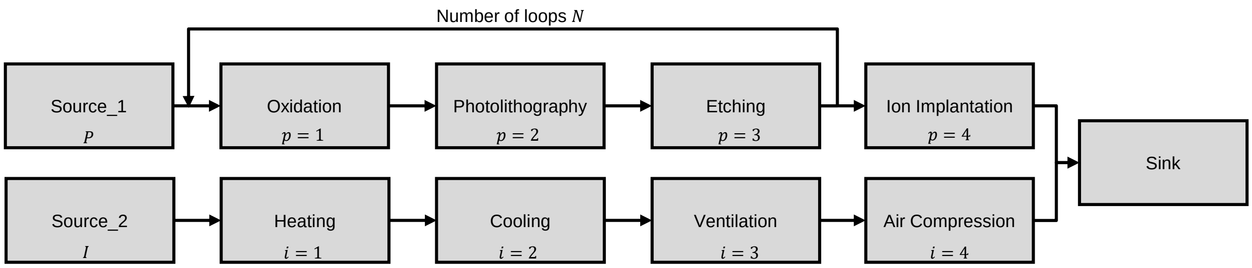

Figure 4: Sequential energy flows of the simulation model.

The lower flow is a fictive stream between the four most critical central infrastructure installations $I = 1, \dots, k$. Both flows are necessary to calculate the energy consumption along with the movement of modeled entities. This implies that in the upper stream, not only production metrics such as work-in-progress, output, and CT are tracked but also the variable energy consumption is calculated at the respective process. At an indicated rate, the fixed energy consumption generation is triggered and calculated additionally. A similar logic is applied to the lower flow representing the central infrastructure installations. Here, the hundred percent fixed energy consumption, which is independent of the production activity, is triggered by one fictive model entity entering the flow after an indicated time interval. Finally, the energy metrics of the model were verified within the model environment and validated with raw company data and qualitative expert knowledge.

5 SIMULATION RESULTS AND DISCUSSION

The proposed model is now enriched by the constructed formula (8) for the Ecological Factor. In addition, to concrete values of the previously unknown energy consumption shares of the eight sub-types, the simulation results deliver the eOC. With parameter variation experiment, the number of input orders is iteratively increased, which leads to the yet-researched increase in utilization. The expected effects on CT, FF, and EF as anticipated by the initial concept presented in section 3 are confirmed. Figure 5 shows the simulative verification of the eOC concept for the simulated fronted fab. It is evident that the initially targeted “elbow” of the original OC is still in focus for optimized production planning and should be even more prioritized to improve the ecological performance by allowing utilization levels to be as high as possible. Before this turning point, both approaches are thus mutually beneficial. High utilization levels only improve the ecological chip performance in terms of energy consumption when the fab operates at fixed consumption shares $\alpha_e >> 0$. Since semiconductor manufacturing with its energy intense cleanroom environment normally reports high levels of fixed energy consumption, the pursuit of high utilizations is economically and ecologically beneficial. The new concept, therefore, serves as an additional justification for the original approach of further reducing the variability α to allow high utilization levels at an acceptable CT. The steep increase after the “elbow”, however, indicates a trade-off between the economic and ecological perspectives. While the energy consumption per chip still decreases, the FF of a fab will heavily increase with rising utilization. Therefore, it is worth taking a closer look at a scenario when compromising full utilization and energy efficiency in exchange for operational performance is less harmful. In times of chip shortage, semiconductor fabs pursue the *warm-steel* approach, which implies constantly keeping machines and infrastructure switched on, to be ready for incoming customer orders. In contrast, allowing for a certain level of switching flexibility by the *cold-steel* mode could be a promising direction for fabs after the crisis. With a re-balanced semiconductor supply chain and enabling a certain "operating state flexibility", machines or even total infrastructure installations could be switched off so that they are only running when there is actual throughput. This would enable a reduction of the fixed energy consumption share α_e which would in turn accept slightly lower levels of utilization in terms of energy efficiency per chip. One could argue that any activity that could potentially lead to a higher system variability α could be compensated, at least from a chip energy efficiency point of view.

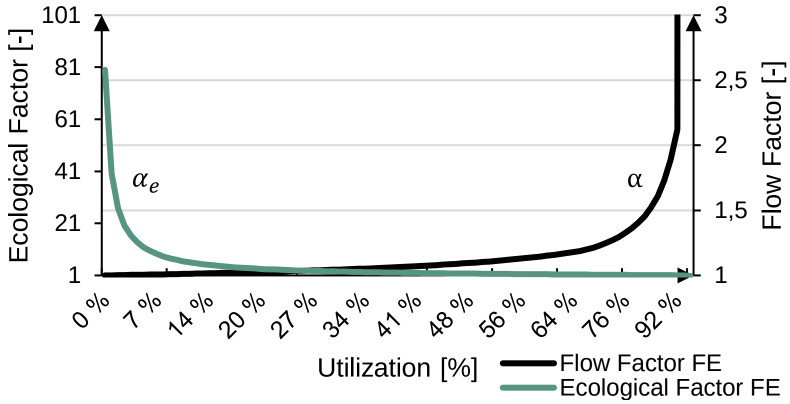

Figure 5: Simulation results of Ecological and Economic Operating Curve for a given α and α_e.

6 CONCLUSION AND OUTLOOK

The semiconductor industry is facing pressure to reduce its extensive energy consumption, which requires transparency on the relationship between energy efficiency and original planning objectives. The new concept of the eOC adds energy efficiency-related aspects to the existing and, so far, only economically motivated concept of the OC. It does not intend to function as a model on its own but is designed to provide an additional ecological view in synergy with the economic view. Simulation results of the constructed curve verify the derived formula for the novel Ecological Factor. The concept extension reveals that until a certain threshold of utilization, economic and ecological objectives mutually benefit each other. For scenarios after this turning point, future structural changes of possible operation modes for fabs get into the focus for which the proposed concept could serve as a basis for discussion. Future research should apply the introduced theoretical concept of the eOC to another wafer fab for further verification and most importantly validation. Additionally, the Ecological Factor could be enriched by other sustainability aspects than energy efficiency. The presented ratio of real to ideal ecological activities might be eligible for considerations such as prevented amounts of environmentally harmful raw materials, shares of components contributing to circular economies or, amounts of funding activities paving the way towards carbon neutrality.

A RELEVANT EQUATION ELEMENTS

Structural element	**Dimension**	**Explanation**
C	*units*	Capacity of a fab or process
c_{RPT}	$[-]$	Variation coefficient of the raw processing time
c_{QT}	$[-]$	Variation coefficient of the queuing time
CT	*months*	Cycle time
$E_{chip,ideal}$	$MWh/chip$	Idealistic energy consumption per chip at 100 % utilization

E_{max}	MWh	Theoretical maximum energy consumption at 100 % utilization
E_{ratio}	$\%$	Ratio of total consumption to maximum possible consumption
$E_{chip,real}$	$MWh/chip$	Real energy consumption per chip at a given utilization level
E_{total}	MWh	Sum of fixed and variable energy consumption for a given utilization level
EF	$[-]$	Ecological Factor
FF	$[-]$	Flow Factor
GR	*units/month*	Going rate or throughput
IA	*months*	Interarrival time
N	*units*	Number of loops in frontend manufacturing
RPT	*months*	Raw process time
QT	*months*	Queuing time
U	$\%$	Utilization
α	$[-]$	(Original) alpha
α_e	$[-]$	Ecological alpha

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