Supply Chain Efficiency: Evaluation of Value Curve-based Flow Efficiency Models

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Master's Dissertation

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Abstract

Effectively managing the trade-off between service level and cost is a critical concern for companies seeking to optimize their supply chain.

During a research project conducted at Hilti, a novel approach to managing this trade-off was developed using value curve-based efficiency calculation and regression analysis.

In the literature, the existing proposals for calculating the efficiency value, known as flow efficiency, lack thorough testing with sufficient case data to assess their validity.

To bridge this gap, this thesis collects item production data for approximately 400 cases and applies an established evaluation framework for the first time.

Initial findings from this study lead to the development of an additional calculation method, which is subjected to the same evaluation as the remaining ones.

The results reveal that two flow efficiency calculation methods demonstrate suitability for the 400 cases analyzed. Additionally, for the approximately 10% of outlying cases, a workaround solution has been devised.

Resumo

Eficiência da Cadeia de Abastecimento: Avaliação de Modelos de Eficiência de Fluxo baseados em Gráficos Valor-Tempo

Gerir efetivamente o compromisso entre o nível de serviço e o custo é uma preocupação crítica para empresas que procuram otimizar a sua cadeia de abastecimento.

Durante um projeto de investigação realizado na Hilti, foi desenvolvida uma abordagem inovadora para endereçar este desafio através do cálculo de eficiência baseado em gráficos valor-tempo e regressões.

Na literatura, as propostas existentes para calcular o valor de eficiência, conhecido como eficiência de fluxo, carecem de testes exaustivos com dados suficientes para avaliar a sua validade.

Para colmatar esta lacuna, esta tese recolhe dados de produção de cerca de 400 casos e aplica, pela primeira vez, um quadro de avaliação estabelecido.

As constatações iniciais deste estudo levaram ao desenvolvimento de um método de cálculo adicional, que será submetido à mesma avaliação que os restantes.

Os resultados revelam que dois métodos de cálculo de eficiência de fluxo demonstram adequação para os 400 casos analisados. Para além disso, para aproximadamente 10% dos casos atípicos, foi concebida uma solução alternativa.

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To all my family who have supported me on my journey, and what a journey it has been. Nothing has been left unachieved due to the lack of your support.

To my brother, you are my greatest source of pride. Thank you for believing in me more than I believe in myself. Thanks for being my guide and inspiration at all times. And to my sister-in-law, thank you for keeping him, and by extension me, on the right track.

To my beloved mom, thank you for your unconditional love and for always listening to my laments. You are my greatest example of resilience. Stay strong, and please forgive my absence and selfishness.

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À minha querida mãe, obrigada pelo teu amor incondicional e por ouvires sempre as minhas lamentações. És o meu maior exemplo de resiliência. Continua forte e, por favor, desculpa a minha ausência e egoísmo.

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"There is nothing either good or bad, but thinking makes it so."

William Shakespeare

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Acronyms and Symbols

BU	Business Unit
CRISP-DM	Cross Industry Standard Process for Data Mining
DEA	Data Envelopment Analysis
DOS	Sourcing Excellence Department
ERP	Enterprise Resource Planning
SAP	System Analysis Program Development (Systemanalyse Programmentwicklung)
SFA	Stochastic Frontier Analysis
RPC	Coefficient of Reproducibility

•	Fully Addressed
○	Partially Addressed

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Chapter 1

Introduction

For the success and competitiveness of companies, it is critical to manage the fundamental trade-off between cost and service level through an appropriate, continuously monitored efficient supply chain setup (Prockl, 2001; Chopra and Meindl, 2006). This trade-off is particularly significant for Hilti, a global direct sales company with a complex supply chain setup.

Companies have relied on methods such as Stochastic Frontier Analysis (SFA) - a parametric approach, or Data Envelopment Analysis (DEA) - a non-parametric approach, to enhance efficiency in their operations (Cooper et al., 2003; Daraio and Simar, 2007; Burger, 2008). However, SFA requires normally distributed data to accurately estimate the production frontier, while DEA struggles to handle noise in the data, thus impacting the reliability of its results (Katharakis et al., 2014; Bauer et al., 1998). Therefore, there is room for alternative approaches that can address these challenges.

To address this gap, a research project proposing a novel approach to quantify efficiency has been conducted by Sieben (2023). This research, which encompasses bachelor‘s (Näf (2015); Wolf (2020)) and master‘s theses (Parlak and Pescalli (2023); Gomes (2021); Klein (2021); Putkivaara (2020); Musacchia (2019); Thampi (2018)), a journal paper (Sieben et al. (2023)) and a doctoral thesis (Sieben (2023)), uses value curves, a depiction of the value as a function of time for each production stage, to calculate a proxy for the efficiency in production and logistic networks which was named by Sieben (2023) as flow efficiency. In addition, this flow efficiency is compared against statistically estimated efficiency values that are computed using performance pricing, a regression-based method in procurement to evaluate purchase prices[1].

For the flow efficiency stream of the research project, Sieben (2023) and (Sieben et al., 2023) have developed the calculation of partial flow efficiency values, corresponding to the value for one specific step, different weighting methods to aggregate these partial flow efficiency values and an evaluation framework, using Bland & Altman and Spearman to apply three efficiency consistency conditions proposed by Bauer et al. (1998) and three more value curve-focused assessment criteria for weighting methods.

[1]The technical standard VDI 2817 provides a comprehensive overview of the performance pricing methods (VDI - Verein Deutscher Ingenieure, 2018)

Since the number of practical cases has been rather limited, this thesis focuses on three main aspects: collecting case data; calculating flow efficiency values according to all available methods; and assessing all methods by applying the evaluation framework. In addition, a novel flow efficiency calculation method was also proposed. The author would like to thank the co-authors of (Sieben et al., 2023), and the other project stakeholders, without whose close cooperation the results would not have been achieved.

1.1 Problem scope

The existing research conducted in the context of bachelor and master theses focused on several topics concerning the usage of value curves to calculate efficiency, such as new calculation methods (Näf, 2015; Sieben, 2023), the application to different product portfolios (Thampi, 2018; Gomes, 2021; Bley, 2022) and, in the case of (Klein, 2021), a systematic comparison between flow efficiency and other efficiency calculation methods (DEA). However, the actual number of underlying case data has been rather limited which constrains a rigorous and data-driven evaluation.

To accomplish this, enhancing the abundance and heterogeneity of data employed for assessing flow efficiency emerged as a crucial imperative. Doing so is only possible by facilitating the accessibility of such data, in order to enhance the insights that stakeholders can gain into the operational dynamics of products along the production lines.

In addition, while the Bland & Altman and Spearman analysis , proposed by Sieben (2023) in his evaluation framework and used in this work, does not require a large number of cases (Mansournia et al., 2020), having a more extensive dataset increases the robustness and reliability of the statistical analysis. Furthermore, by testing the different models in an extensive and diversified dataset strengthens the validity of the conclusions drawn and enhances the significance of the research project outcomes.

1.2 Problem statement

Based on the interest of better understanding and improving existing flow efficiency calculation methods and assess their comparative performance, the research questions are as follows:

- How to collect case data efficiently?
- How do the flow efficiency calculation methods perform in comparison to each other, and can a particular weighting approach be recommended using the evaluation framework?

To answer these questions, a comprehensive literature review was conducted to identify and analyze existing flow efficiency calculation methods (with a focus on the work conducted in the project so far), and relevant data from Hilti's operations and products were collected. Using these case data, existing models were evaluated and compared in order to understand their relative performance in a practical setup.

1.3 Project background

As pointed out in Section 1.1, the thesis, that started in February, 2023, was embedded in a bigger project with the aim of developing a novel, value-based method to assess the appropriateness of supply chain setups. The author was during that period an intern at Hilti, and together with a team of Hilti's experts and managers, carried out a study with the goal of applying Sieben (2023) evaluation framework to different existing proposals to calculate flow efficiency. Data collection, treatment, and analysis tasks were carried out with the intention of advancing the field of study and the current research project by contributing to the literature on flow efficiency calculation.

1.4 Dissertation structure

The dissertation structure is based on the methodology proposed by Ulrich (1981), given its usefulness to handle a practical problem in a formal and scientific way, with adaptations that better suit the needs of this specific project. Figure 1.1 shows the relation between Ulrich's original framework and the structure of this document.

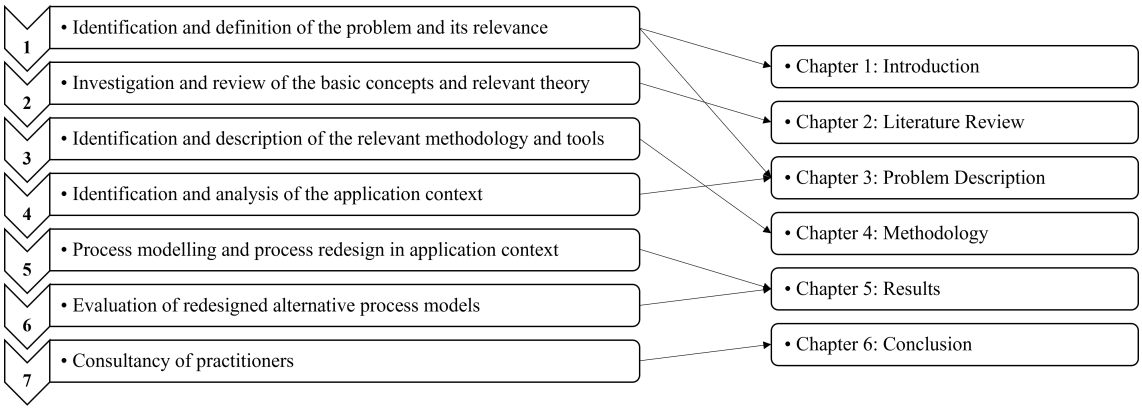


Figure 1.1: Dissertation's structure. Source: Ulrich (1981) (modified)

Besides this introduction, the structure of this study is as follows. Chapter 2 presents the main concepts and the gap in the extant literature about the problem.

Chapter 3 details the problem and what needs to be studied to address the research questions.

Chapter 4 covers the approach selected to fill the current literature gap, introducing the research scope, the related procedures, and the actions that need to be taken to support that approach.

Chapter 5 presents the main results and the following conclusions. This chapter also highlights the practical and theoretical contributions of the study and Chapter 6 covers the model's transferability, main limitations, and potential future developments.

Chapter 2

Literature review

A literature review has been conducted with the identification of supply chain management best practices and the current state-of-the-art in supply chain efficiency measuring methods. Also, adjacent topics are presented such as supply chain management and working capital management.

Based on this review, terms and pertinent theoretical concepts are dissected for clarity throughout the dissertation. The next chapter provides a detailed explanation, along with pertinent formulae, figures, and tables, of the techniques utilized in the methodology creation process that will then be put into practice with Hilti's case study.

2.1 Supply chain management

The planning and management of all sourcing and procurement, conversion, and logistics management tasks are included in supply chain management which also involves coordination and collaboration between channel partners — suppliers, middlemen, third-party service providers, and customers. Supply chain management essentially unifies supply and demand control within and among businesses. (CSCMP, 2013)

Forrester (1958) was the first to introduce the concept of supply chain management in order to reveal the dynamics of supply chains' responses to changes in demand. The author has shown that the dynamic complexity involved in moving demand from end users down a supply chain to manufacturers and material suppliers caused a distortion in demand patterns. One of the most remarkable findings of the study was the discovery of the dependency between supply chain stakeholders regarding information data flows, as well as the time related impacts inherent in the phenomenon's dynamics.

Long before it became a strategic tool or a competitive advantage, supply chain managers recognized the value of information and time (Li et al., 2006). It is crucial to be able to reach the markets with the right products faster than the competition, to be able to satisfy customer demands and to make sure that supply chains can be synchronized to meet demand fluctuations (Stern and Stalk Jr., 1998). By reducing the planning loop in the product development cycle and streamlining

supply chain processes, today's businesses compete with flexible production and rapid-response systems, boosting diversity and creativity to unprecedented levels (Mason-Jones et al., 2000).

Supply chain management has an integrating role of connecting key business operations and business processes both within and across organizations to create an effective business model. It promotes coordination of processes and activities with and beyond marketing, sales, product design, finance, and information technology and includes all logistics management activities as well as manufacturing operations (CSCMP, 2013).

Supply chain management goal is to increase a company's ability to lower costs, order and lead times, enhance the efficiency of using raw materials, and increase distribution capacity (Heizer, 2008). This is important for businesses since it enhances the efficiency of production processes and makes companies more competitive (Kaynak, 2003).

2.2 Supply chain efficiency

Prior to addressing efficiency in supply chains, it is worth providing a couple of basic definitions.

(Cooper et al., 2003) defines efficiency - contrary to productivity - as a relative measurement of the output-input ratio of a system, e.g., a production line. Relative means, that an efficiency value always has to be compared with the efficiency values of other systems (Dyckhoff, 2003). If a system can produce more output or the same output with less input than other systems, it is called efficient (Scheel, 2000)

2.2.1 Product effects in supply chain efficiency

Fisher (1997) was one of the first authors to provide a framework to select the optimal technique for their specific supply chain management strategy. This framework helps to understand the nature of product demand and to create a supply chain to meet this demand. There are two categories of products: those that are mostly inventive and those that are largely utilitarian. According to Fisher (1997), a physically efficient supply chain approach is better for functional items, while a supply chain strategy that is responsive to the market works best for innovative products. Research in supply chain management quickly transitioned from the original Fisher's principles to the analysis of changes of Fisher's original framework as a result of the concept of supply chain product alignment (Harris, 2007). Fisher's framework matrix for linking supply chains with goods is shown in Figure 2.1.

Huang et al. (2002) proposed that the selection of the type of supply chain depends on the type of product made by the company. The products can be innovative, hybrid, or functional, and the supply chains can be lean, agile and hybrid. Figure 2.2 shows the matrix with the respective matches between the kind of item and the desired supply chain configuration type.

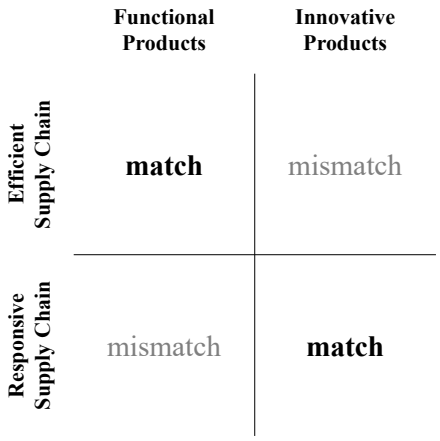


Figure 2.1: Fisher (1997) divides products into two categories and defines the supply chain configuration to match them in the most effective way. Source: Fisher (1997) (modified)

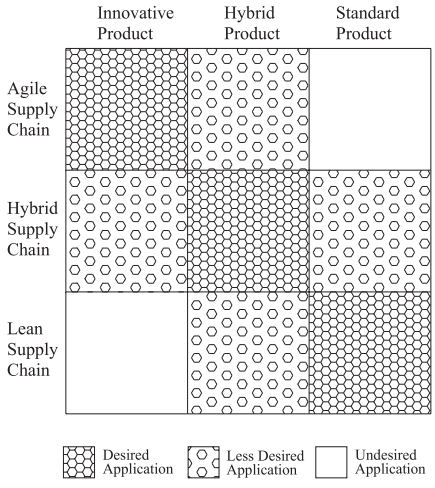


Figure 2.2: Huang et al. (2002) extend Fisher (1997) principle to three types of products and supply chain strategies. Source: Huang et al. (2002)

2.2.2 Cost-responsiveness efficiency frontier

Understanding the supply chain and placing it on the responsiveness spectrum is an important stage in attaining strategic alignment (Chopra and Meindl, 2006). The cost-responsiveness efficient frontier is a curve that shows the lowest possible cost for a given level of responsiveness. In other words, it represents the cost-responsiveness performance of the best supply networks, and therefore not all businesses can operate at the frontier of efficiency. The responsiveness and cost performance of a company that is not on the efficient frontier can both be enhanced by heading in that direction. A company on the efficient frontier, however, can only increase its responsiveness by raising costs and losing efficiency (Chopra and Meindl, 2006). Thus, there is a trade off between efficiency and responsiveness. Businesses operating at the efficient frontier are also constantly enhancing their procedures and updating technology in an effort to move the efficient frontier itself. The visual representation of the cost-responsiveness efficiency frontier is shown in figure 2.3.

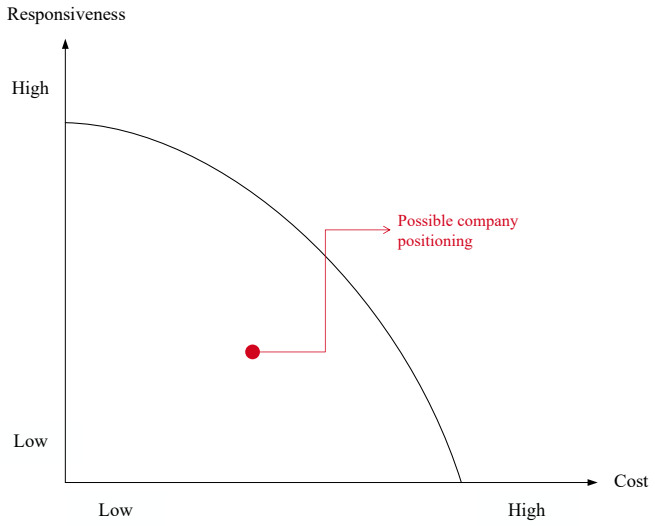


Figure 2.3: Cost-responsiveness efficiency frontier shows that companies that are not in the frontier can incresae both cost and responsiveness performance, while companies on the frontier can only increase its responsiveness by raising costs and losing efficiency. Source: Chopra and Meindl (2006) (modified)

A strategic decision for every supply chain is how responsive the company intends to be, taking into account the trade-off between cost and responsiveness. Some supply chains focus on the lowest cost, whereas others just focus on responsiveness. The responsive supply chain is set up to successfully handle both demand and supply volatility, while in contrast, an effective supply chain reduces costs by reducing part of its flexibility to adapt to different environments.

2.3 Working capital management

The profitability of businesses is significantly impacted by how working capital is managed and poor and ineffective working capital management causes money to be invested in idle assets, which decreases a company's liquidity and profitability (Reddy and Kameswari, 2004). Planning current assets and liabilities in a way that removes the danger of being unable to fulfill short-term commitments and prevents excessive investment in these assets is essential to effective liquidity management. One of the most significant measures of liquidity that impact profitability is the cash conversion cycle (Days of Inventory on Hand + Days of Sales Outstanding - Days of Payables Outstanding) and, according to Eljelly (2004) profitability and liquidity metrics like the current ratio and cash gap (Average Collection Period - Average Payment Period) have a negative correlation.

According to Blinder and Maccini (1991), current assets as large inventories help minimize production process disruptions and commercial loss owing to product scarcity, as well as lower supply prices and price variations. Additionally, they enable businesses to provide better customer service and prevent high production costs brought on by significant production fluctuations (Schiff and Lieber, 1974).

On the other hand, other kind of current assets such as trade credit may also boost a company's sales because it can act as an effective price reduction (Brennan et al. (1988); Petersen and Rajan (1997)), as it encourages customers to purchase goods during periods of low demand, strengthens long-term supplier-customer relationships (Wilner, 2000).

Emery (1984) states that trade credit outperforms marketable assets as a short term investment. Also, working capital may serve as a reserve for emergency liquidity, protecting against any cash shortages in the future. Last but not least, Wilner (2000) demonstrate from the perspective of accounts payable that a business may receive substantial discounts for early payments.

However, there are also potential negative effects of working capital investment that could have a detrimental effect on the company value at specific working capital levels (Deloof, 2003). These are the kind of effects that matter the most for supply chain management since they are usually related to the maintenance of high inventory levels leading to expenses like warehouse rent, insurance, and security fees, all of which tend to go higher as the inventory levels do (Lee and Billington, 1992). A higher working capital level also means that businesses must borrow more capital, which comes with opportunity costs and financing expenses. Also, companies with larger levels of working capital also experience higher rates of interest deductions as a result, which increases credit risk (Kieschnick et al., 2013). In addition, it is more common for businesses to experience financial difficulties and the prospect of bankruptcy as working capital rises. Finally, maintaining high working capital levels results in money being locked up what may also limit a company's capacity to engage in other value-adding initiatives (Deloof, 2003).

These favorable and unfavorable effects show that trade-offs are present in working capital decisions. As a result, it is anticipated that businesses will have a working capital level that balances these costs and advantages while maximizing their value. In particular, corporate performance will improve when working capital rises up to a certain threshold. On the other hand, one may

expect that the relationship between working capital and performance will turn negative beyond this optimum (Deloof, 2003). There is an ideal level of working capital investment that strikes a balance between costs and benefits and maximizes a firm's performance.

Therefore, managers would prefer to invest more in working capital at lower levels of working capital in order to enhance sales and the discounts for early payments received from suppliers. A bigger investment, however, starts to have a negative impact on value creation at a certain level of working capital because of the increased interest costs and therefore higher risk of bankruptcy and credit risk for businesses. Therefore, firm managers should strive to maintain the optimal level and try to prevent any deviations from it that reduce firm value.

2.4 Value curves

Porter (2001) work on value chain analysis and competitive advantage has provided a foundation for understanding the value creation activities within an organization and the role of the supply chain in delivering value to customers.

A value curve for the supply chain represents the perceived value or benefit derived by customers or stakeholders at different stages or activities within the supply chain process (Porter, 2001). It visualizes the relationship between supply chain activities and the value delivered to customers. As shown in the Figure 2.4, the horizontal axis represents the time at which activities occur, such as sourcing, production, inventory management, transportation, and customer service. The vertical axis represents the perceived value or utility provided by the supply chain at each stage.

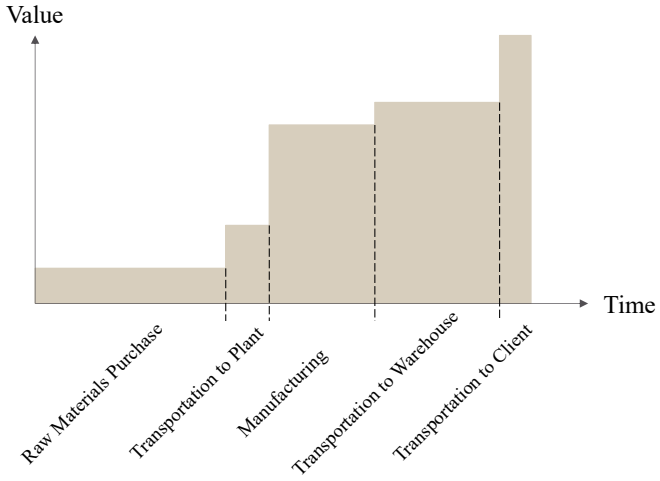


Figure 2.4: Example of a 5-step value curve representing different stages of the supply chain. Source: The author

By examining the value curve for the supply chain, businesses can identify areas of strength and weakness. The analysis enables them to focus their efforts on improving and optimizing the stages of the supply chain that deliver the highest value to customers. Understanding customer

needs and preferences empowers businesses to align their supply chain activities effectively, resulting in increased customer satisfaction and competitive advantages. This may involve streamlining processes, reducing lead times, improving product quality, or enhancing customer service. By tailoring the supply chain to meet customer preferences, businesses can differentiate themselves in the market and foster stronger customer loyalty (Kopczak and Johnson, 2003).

Furthermore, analyzing value curves for the supply chain helps identify cost drivers and areas where costs can be reduced without compromising customer value. This enables businesses to improve supply chain efficiency, eliminate waste, and optimize resource allocation. Cost optimization within the supply chain can also result in enhanced profitability and a competitive cost advantage (Li et al., 2006).

In practice, value curves may help in strategic decision-making, process improvement, and resource allocation. Businesses can make informed choices about investments in supply chain activities, identify areas for collaboration or partnerships, and prioritize continuous improvement efforts (Porter, 2001).

Given the wide use within industry since the second half of the eighties (Zachau, 1995), the literature is remarkably scarce (Sieben, 2023). Next to Porter (2001), (Danert, 1988) is the most prominent publication, pointing out that operational improvements by means of shorter lead times (a), cost reductions (b) and more productive processes (c), respectively, are reflected by a compression of the value curve (Danert, 1988; Schulte, 1999). Furthermore, a couple of doctoral theses picked up the topic (Slomka, 1989; Herbrüggen, 1991; Zachau, 1995), but merely qualitatively without providing further quantification methods.

2.5 Value curves based flow efficiency calculation

The flow efficiency as a term was proposed by Sieben (2023) and represents the resulting value of calculating the efficiency of a value curve. Nienhaus (2004) was the first to point out that the area occupied by the value curve graph and the total area could be used quantitatively. Later, within the context of Sieben's research project, several weighting approaches to calculate flow efficiency were proposed and several authors, i.e., (Näf, 2015; Thampi, 2018; Wolf, 2020; Gomes, 2021; Bley, 2022; Parlak and Pescalli, 2023) contributed to the literature in this area with either new calculation methods (Näf, 2015; Sieben, 2023), the application to different product portfolios (Thampi, 2018; Gomes, 2021; Bley, 2022) and, in the case of (Klein, 2021), a systematic comparison between flow efficiency and other efficiency calculation methods (DEA). This section covers the relevant contributions.

2.5.1 Nienhaus' efficiency model

Nienhaus (2004) mentioned in a sidenote of his doctoral dissertation, that the efficiency (to which we refer here as flow efficiency) could be derived from value curves. In this model, the flow efficiency of a supply chain represented through a value curve is equal to the difference between

one and the quotient between the area occupied by the value curve graph and the total area, as shown in Figure 2.5 and Equation 2.1.

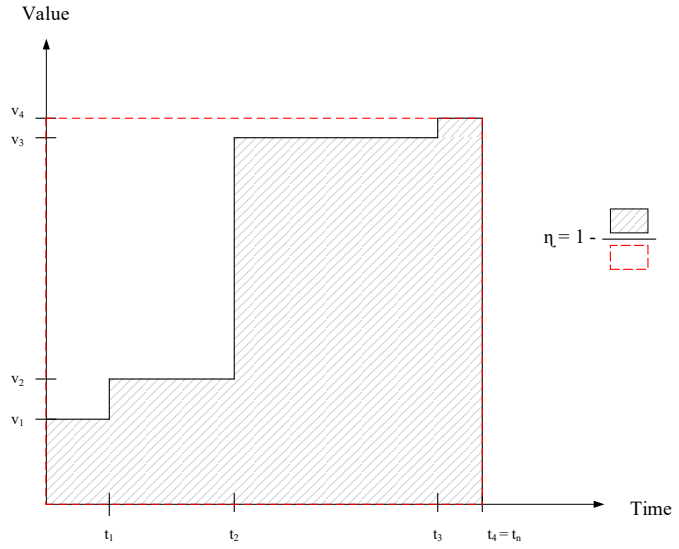


Figure 2.5: Graphical representation of Nienhaus' model. Source: The author and Sieben (2023)

$$\eta = 1 - \frac{\sum_{i=1}^{n} v_i \times (t_i - t_{i-1})}{t_n \times v_n} \tag{2.1}$$

The main idea behind this method is that the less the filled area in the graph, the less the capital employed and therefore the higher efficiency. However, this is not true for any possible scenario, as suggested by Näf (2015). One of the cases is when the first step of the value curve has longer duration and low value compared to other steps. This limitation will be exploited further in this work, including a visual representation of the implied challenge.

2.5.2 Näf's model

Recognizing the limitation in Nienhaus' model, Näf (2015) (the first bachelor's thesis of the project, in which this thesis is also embedded) developed an alternative method that tries to identify when we are in the presence of such cases and, if so, ignore this step in the value chain efficiency calculation. To do this, he proposed - in a heurisic way - that if the length of the first step of the curve is four times longer than the remaining steps, then the first step is eliminated from the calculation and the Nienhaus method is used only for the remaining steps. This method can be described by the Equation 2.2.

$$\eta = 1 - \frac{\sum_{i=1}^{n} v_i \times (t_i - t_{i-1})}{t_n \times v_n} \quad with \quad \frac{t_i}{t} \geq z \times \frac{v_i}{v} \tag{2.2}$$

2.5.3 Sieben's models

Sieben (2023) proposed other approaches such as calculating the partial flow efficiency for each of the steps of the value curve based on the ratio between the angle defined by the step *i* and the optimal angle ($\frac{\pi}{2}$), which would represent the creation of all the value instantly. This concept is defined as pointer-based determination of partial flow efficiency and is graphically represented in Figure 2.6.

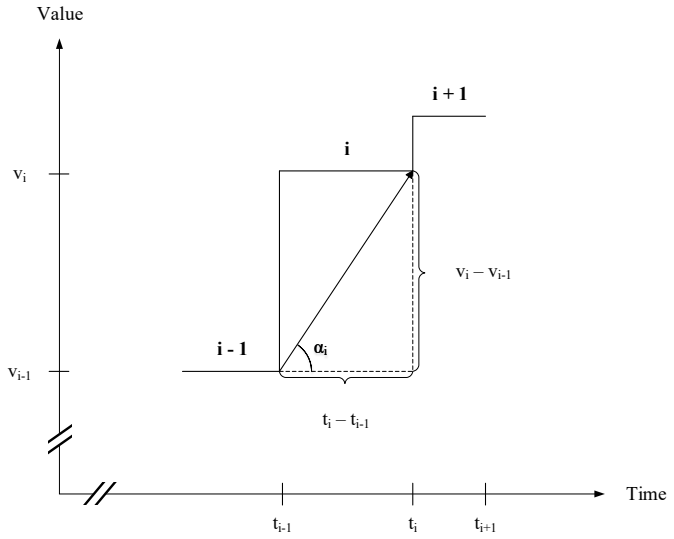


Figure 2.6: Partial flow efficiency η_i is correlated with the angle α_i. Source: The author and Sieben (2023)

Its mathematical formulation, presented in Equation 2.3, relies on the inverse tangent function, known for its numerical stability and ability to produce accurate results even with small perturbations in the input. Its compatibility with finite precision arithmetic makes it a reliable and suitable choice for empirical analysis through numerical calculations using the computer's finite precision arithmetic (Sieben, 2023).

$$\eta_i = \arctan \frac{\frac{v_i - v_{i-1}}{v_n}}{\frac{t_i - t_{i-1}}{t_n}} \cdot \frac{2}{\pi} \tag{2.3}$$

An efficient step - a step in which a lot of capital is added in a short period of time - in the initial phase of the supply chain will have the opposite effect to the one intended for an efficient process. In addition, the efficiency of a step that has a significantly longer duration than all the others may have a much larger impact on total flow efficiency than the remaining steps.

Considering this and the fact that a high flow efficiency at a later point of the supply chain has a significantly bigger positive effect on efficiency than at one of the early stages, the models created by Sieben (2023) use weighting approaches that transpose into a mathematical formulation the relative importance of each of the steps of the value curve.

Sieben (2023) proposed eight different weighting models: value-based, time-based, combined value-time-based, value vector-based, horizontal slack-based, vertical slack-based, exponential and gravitational distance. In addition, Sieben (2023) also came up with two novel "Total Value" approaches[1]. As pointed out by (Sieben, 2023) in his PhD thesis, the "Total Value" approaches and the gravitational distance weighting are the result of collaborative work with the author of this thesis.

2.5.3.1 Value-based weighting

In this approach, the weighting of partial flow efficiencies is based on their respective value added shares. Under this scheme, a greater significance is attributed to a particular partial flow efficiency when its corresponding value added share is higher. This results in the Equation 2.4 and is graphically represented in Figure 2.7.

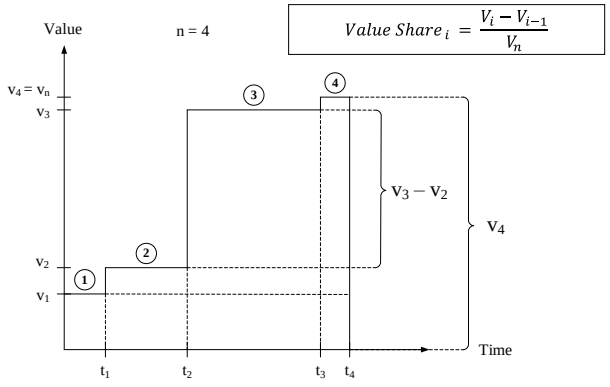


Figure 2.7: Representation of value-based weighting. Source: The author and Sieben (2023)

$$\eta = \sum_{i=1}^{n} \left\{ arctan\left(\frac{t_n \cdot (v_i - v_{i-1})}{v_n \cdot (t_i - t_{i-1})} \right) \cdot \frac{2 \cdot (v_i - v_{i-1})}{\pi \cdot v_n} \right\} \tag{2.4}$$

2.5.3.2 Time-based weighting

In the second approach, the weighting of individual flow efficiencies is based on their respective time shares. Within this framework, greater importance is assigned to a particular partial flow efficiency when its corresponding time fraction is higher. Equation 2.5 shows how this is translated into a mathematical model and Figure 2.8 shows the visual representation.

[1] Total value as defined by Sieben (2023) refers to models that consider the all value curve configuration rather than focusing on individual steps.

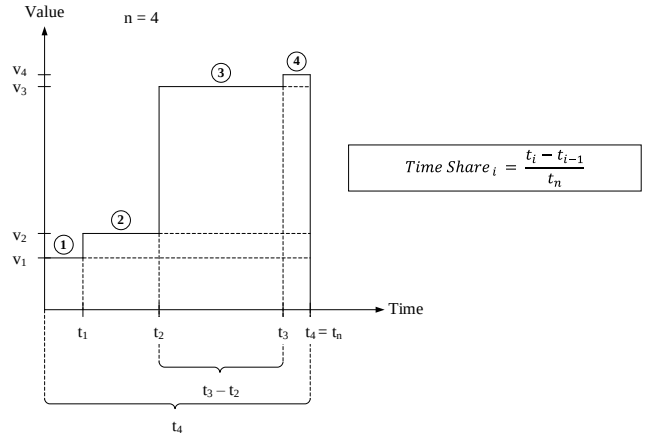


Figure 2.8: Representation of time-based weighting. Source: The author and Sieben (2023)

$$\eta = \sum_{i=1}^{n} \left\{ arctan\left(\frac{t_n \cdot (v_i - v_{i-1})}{v_n \cdot (t_i - t_{i-1})} \right) \cdot \frac{2 \cdot t_i}{\pi \cdot t_n} \right\} \tag{2.5}$$

2.5.3.3 Combined value-time-based weighting

The two aforementioned weighting approaches can be combined by integrating the time and value components. This combination results in a proportional weighting for individual flow efficiencies, aligning with the value curve surface. In this approach, the relative importance of a partial flow efficiency is determined by considering both its time share and value added share concurrently. Figure 2.9 and Equation 2.6 show this approach.

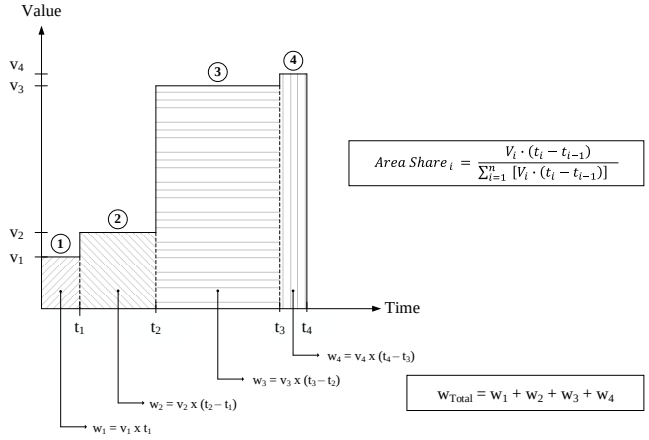


Figure 2.9: Representation of combined value-time-based weighting. Source: The author and Sieben (2023)

$$\eta = \sum_{i=1}^{n} \left\{ arctan\left(\frac{t_n \cdot (v_i - v_{i-1})}{v_n \cdot (t_i - t_{i-1})} \right) \cdot \frac{2 \cdot v_i \cdot (t_i - t_{i-1})}{\pi \cdot \sum_{i=1}^{n} [v_i \cdot (t_i - t_{i-1})]} \right\} \tag{2.6}$$

2.5.3.4 Value vector-based weighting

It is also possible to combine the time and value components of each vector that composes the steps of the overall process by projecting the partial efficiency vector onto the vector representing the average flow efficiency. In this scenario, the share of the length of the projection of each partial efficiency vector in the overall one would represent the weight of the step in the overall efficiency. In this case, Figure 2.10 and Equation 2.7 show the graphical and mathematical formulation of this approach.

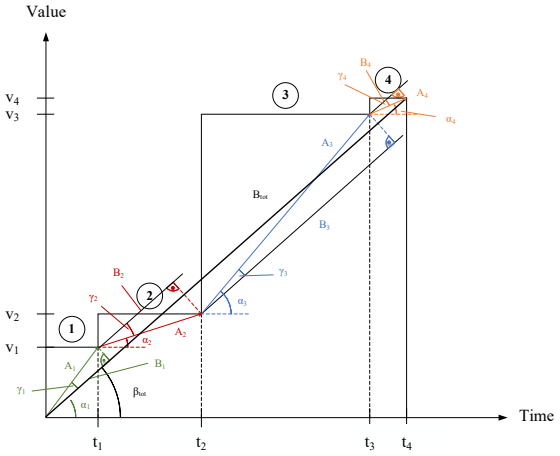


Figure 2.10: Representation of value vector-based weighting. Source: The author and Sieben (2023)

$$\eta = \sum_{i=1}^{n} \left(\eta_i \cdot \frac{\sqrt{(v_i - v_{i-1})^2 + (t_i - t_{i-1})^2} \cdot \cos\left(\left| \arctan\left(\frac{v_n \cdot (t_i - t_{i-1}) - t_n \cdot (v_i - v_{i-1})}{t_n \cdot (t_i - t_{i-1}) + v_n \cdot (v_i - v_{i-1})} \right) \right| \right)}{\sqrt{(v_n^2 + t_n^2)}} \right) \tag{2.7}$$

2.5.3.5 Horizontal slack-based weighting

A fundamentally different approach entails considering the horizontally downstream areas originated by a production step when determining the weighting. With this approach, despite a high partial flow efficiency, a substantial early value added step negatively impacts the overall total flow efficiency. Mathematically, this is translated by the negative impact that the respective horizontal residual area and the total horizontal residual area have in the overall summation. This results in the Equation 2.8 and is graphically represented in Figure 2.11

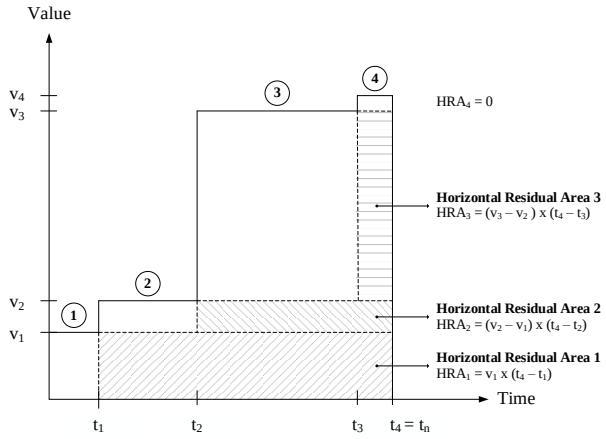


Figure 2.11: Representation of horizontal slack-based weighting. Source: The author and Sieben (2023)

$$\eta = \sum_{i=1}^{n} \left\{ \left[arctan\left(\frac{t_n \cdot (v_i - v_{i-1})}{v_n \cdot (t_i - t_{i-1})} \right) \right] \cdot \frac{2}{\pi} \cdot \left[1 - \frac{(v_i - v_{i-1}) \cdot (t_n - t_i)}{\sum_{i=1}^{n} \left((v_i - v_{i-1}) \cdot (t_n - t_i) \right)} \right] \right\} \tag{2.8}$$

2.5.3.6 Vertical slack-based weighting

Instead of considering the horizontal residual areas, an alternative is using the vertical residual areas. In this case, a high partial flow efficiency directly contributes to a positive effect on the underlying surface, therefore the respective vertical residual surface should be positively related to the total vertical residual surface. This is visually represented in Figure 2.12 and translated by Equation 2.9.

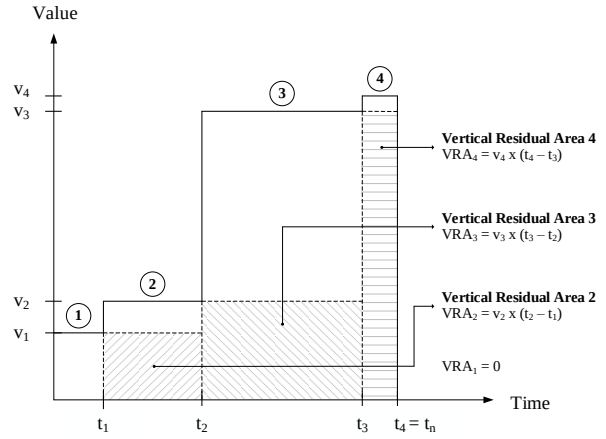


Figure 2.12: Representation of vertical slack-based weighting. Source: The author and Sieben (2023)

$$\eta = \sum_{i=1}^{n} \left\{ arctan\left(\frac{t_n \cdot (v_i - v_{i-1})}{v_n \cdot (t_i - t_{i-1})} \right) \cdot \frac{2 \cdot v_{i-1} \cdot (t_i - t_{i-1})}{\pi \cdot \sum_{i=1}^{n} \left(v_{i-1} \cdot (t_i - t_{i-1}) \right)} \right\} \tag{2.9}$$

2.5.3.7 Exponential weighting

This weighting combines aspects of the two preceding residual value methods, incorporating a heuristic exponential function that assigns greater weight to later stages. This exponential function is characterized by the exponent factor k, that weights the partial flow efficiency according to the step number and the total number of steps (n), as described in Equation 2.10 and shown in Figure 2.13. Considering that both the exponential factor (k) and the number of steps (n) influence the weighting ratio between the first and n^{th} stage, the factor k is incorporated and adjusted in accordance with the number of steps (n).

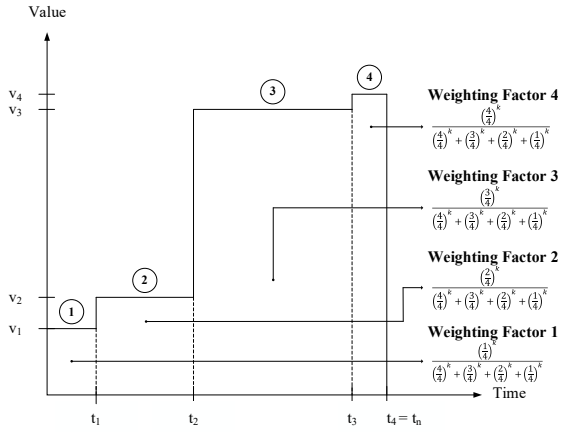


Figure 2.13: Representation of exponential weighting. Source: The author and Sieben (2023)

$$\eta = \sum_{i=1}^{n} \left\{ arctan\left(\frac{t_n \cdot (v_i - v_{i-1})}{v_n \cdot (t_i - t_{i-1})} \right) \cdot \frac{2}{\pi} \cdot \left(\frac{i}{n} \right)^k \right\} \cdot \frac{1}{\sum_{i=1}^{n} \left(\frac{i}{n} \right)^k} \tag{2.10}$$

2.5.3.8 Gravitational distance weighting

This weighting method uses the distance between the total flow efficiency vector and the centroid of the step as the weighting mechanism. Based on this, steps that are further away from the average flow efficiency will contribute more to the overall efficiency than steps in which the centroid coincides with or is close to the average at that point in time. This fictitious value is the result of multiplying the mid point in time of each step by the tangent of β_{total} which represents the average flow efficiency. Steps that deviate significantly from the average efficiency are the real drivers of low or high efficiency.

Figure 2.14 represents the necessary variables used in the mathematical formulation.

From a mathematical perspective, the distance d_i for each step i can be calculated using Equation 2.11:

$$d_i = \left\| \left(\frac{t_i + t_{i-1}}{2} \cdot \tan \beta_{tot} \right) - \frac{v_i}{2} \right\| \tag{2.11}$$

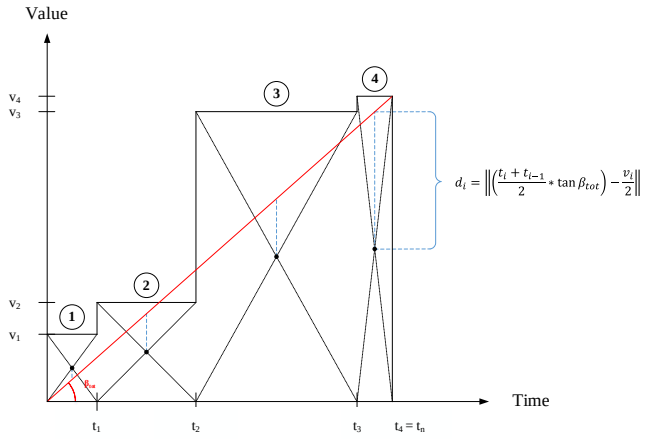


Figure 2.14: Representation of gravitational distance weighting. Source: The author and Sieben (2023)

Based on that, the mathematical formulation to calculate the total flow efficiency is given by Equation 2.12.

$$\eta = \sum_{i=1}^{n} \left[\frac{\left\| \left(\frac{t_i + t_{i-1}}{2} \cdot \tan \beta_{tot} \right) - \frac{v_i}{2} \right\|}{\sum_{i=1}^{n} \left\| \left(\frac{t_i + t_{i-1}}{2} \cdot \tan \beta_{tot} \right) - \frac{v_i}{2} \right\|} \cdot \eta_i \right] \tag{2.12}$$

2.5.3.9 Gravitational distance total value

The Gravitational Total Value method extends the basis of Gravitational Distance Weighting by emphasizing the significance of the average efficiency fictitious point's distance from the centroids at each step of the value curve.

However, it introduces two considerations. Firstly, it adopts a holistic approach referred to as "Total Value," which considers the overall configuration rather than focusing on individual steps of the process. Secondly, it recognizes the relevance of the relative position between the centroid and the average efficiency point, emphasizing non-absolute values. To calculate flow efficiency, the method sums up all the values and divides them by the maximum possible distance. In absolute terms, the maximum distance is determined by multiplying the final step value by the number of steps minus one, however, since the value can be either positive or negative, the overall range is two times that distance $((n-1) \cdot v_n)$. In the nominator, the absolute value of the maximum negative distance was added to make sure that all the efficiencies are between 0 and 1.

Based on this, the total flow efficiency can be calculated using Equation 2.13.

$$\eta = \frac{\sum_{i=1}^{n} \left(\frac{t_i + t_{i-1}}{2} \cdot \tan \beta_{tot} - \frac{v_i}{2} \right) + (n-1) \cdot v_n}{2 \cdot (n-1) \cdot v_n} \tag{2.13}$$

2.5.3.10 Regressive gravitational distance total value

The last method using the centroids of the steps also adopts a Total Value approach. In this case, the centroid data points are subjected to a least squares regression analysis, fitting a regression line

without an intercept term. The slope of this regression line, denoted as β_{Reg}, is obtained by taking the arctangent of the regression slope.

Subsequently, the difference between the total slope (β_{total}) and the slope of the regression line (β_{Reg}) is calculated, resulting in β_{Eff}, the flow efficiency. This value serves as a proxy for evaluating the overall process efficiency with the expectation that an increase in β_{Eff}, indicating that a larger deviation of the regression line from the average flow efficiency, corresponds to a higher process efficiency.

Figure 2.15 shows the Regressive Gravitation Distance Total Value representation.

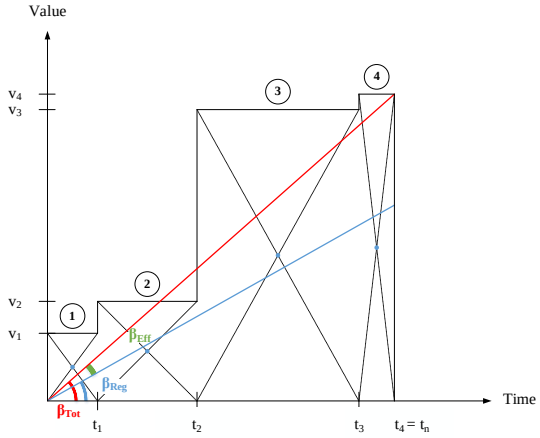


Figure 2.15: Representation of regressive gravitational distance total value. Source: The author and Sieben (2023)

2.6 Consistency conditions of efficiency measures

Bauer et al. (1998) studied efficiency measurement models evaluation and proposed a set of consistency requirements for the efficiency indicators. The efficiency estimates reveal consistency of levels, ranks, and the determination of the best and worst performers by complying with these requirements. They should also be consistent over time, compatible to competitive market circumstances, and reasonably correlate with traditional performance indicators related to supply chain management. Six different criteria make up the list of requirements: Conditions (i), (ii), and (iii) are especially pertinent in a supply chain setting.

According to condition (i), efficiency ratings produced from various methodologies must have equivalent statistical qualities, including means, standard deviations, and other distributional traits. A rigorous performance evaluation is made possible by this criterion, which guarantees that the efficiency estimates may be meaningfully compared.

The salient feature of condition (ii) pertains to the need for diverse methodologies to yield rankings of observations that are relatively consistent with one another. This requirement underscores the necessity for the rankings generated by different approaches to be comparable, providing efficient comparisons and empowering decision-makers to pinpoint supply-chain inefficiencies

or potential areas for improvement.

The significance of consistently identifying "best efficiency" and "worst efficiency" across various methodologies is condition (iii) focus. This implies that the techniques should identify the same processes as exemplifying exceptional or inferior performance. This facilitates informed decision-making and process improvement initiatives.

A foundation for assessing efficiency initiatives is offered by these mutual-consistency criteria (i), (ii), and (iii). Meeting these requirements can produce coherent answers to performance assessment questions.

2.6.1 Sieben's Evaluation Framework

(Sieben, 2023)[2] uses Bland & Altman as well as Spearman to apply Bauer et al. (1998) consistency conditions. Furthermore, he defines three value curve evaluation criteria, i.e., the "mirror condition" to identify obviously faulty partial flow efficiency aggregations, the "time increment condition", which addresses unintended flow efficiency gains through extending the duration of early stages, and the "value decrement condition", which, as pointed out by Sieben (2023), is the result of collaborative work with the author of this thesis, that addresses another obviously faulty efficiency gain in the case of a decreasing value at a production step.

Given the importance of the evaluation framework for this work, it will be further discussed in the methodology in Section 4.5.

2.7 Data analysis formal methods

As pointed out in the previous section, the statistical methods of Spearman‘s coefficient analysis and the Bland-Altman analysis to understand complex relationships in datasets are essential for this thesis. Therefore, the author will explain those in the following two subsections.

2.7.1 Spearman's coefficient analysis

When analyzing the relationship between two variables, it is often important to assess not only the linear relationship but also the consistent directional relationship between them, especially when the data may not follow a specific pattern or when outliers are present. A monotonic relationship implies that as the value of one variable increases, the value of the other variable either consistently increases or consistently decreases (Schober et al., 2018). In other words, there is a systematic pattern of change in one variable as the other variable changes (Akoglu, 2018).

Spearman's correlation coefficient provides a non-parametric measure that evaluates the relationship between variables based on their ranks rather than their actual values (Schober et al., 2018). This makes it more robust to outliers and suitable for assessing non-linear relationships, meaning the rate or pattern of change between the variables may vary, but the overall direction remains consistent.

[2](Sieben et al., 2023) provides an English version.

There are two types of monotonic relationships:

- **Monotonic increasing:** as the values of one variable increase, the values of the other variable also increase, or at least they do not decrease.
- **Monotonic decreasing:** as the values of one variable increase, the values of the other variable decrease, or at least they do not increase.

Spearman's Coefficient analysis has some drawbacks, especially the fact that cannot capture complex non-monotonic relationships or patterns. In addition, Spearman's coefficient only measures the relationship between two variables which means it does not account for potential confounding variables or consider multivariate relationships. Finally, since it uses ranks instead of actual values, it does not consider the magnitude or distance between observations. More broadly, being a correlation analysis, it provides a link between variables which just happen to occur together, without having an association in between (Özgür Doğan, 2018).

2.7.2 Bland-Altman analysis

Bland-Altman analysis is used when we have two measurement techniques or observers that are expected to provide similar results but may differ due to various factors Mansournia et al. (2020). The analysis is used to understand the overall degree of agreement or disagreement and to identify any systematic bias or proportional differences between the two measurement techniques.

To understand these differences, the values obtained from the two measurements are plotted against the average of the measurements, as shown in Figure 2.16. Then, the upper and lower bounds of the difference are calculated, based on the 95% confidence level and summary statistics, such as the mean difference and limits of agreement, are computed to provide quantitative measures of the level of agreement between the two methods.

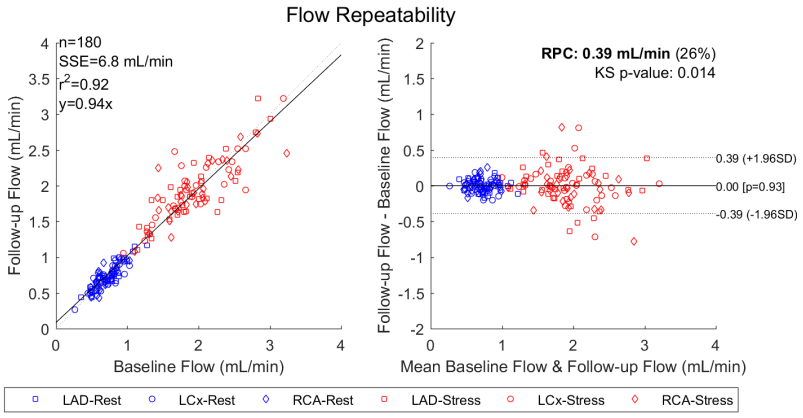


Figure 2.16: Example of Bland & Altman plot obtained from Klein (2023) demo code. Source: Klein (2023)

This analysis estimates accuracy and interchangeability of the measurements. Furthermore, it can help identify visually outliers or extreme differences between the measurements.

However, the Bland and Altman analysis has some limitations (Giavarina, 2015). Firstly, the sample size and the range and distribution of the average values affects the accuracy of the analysis, as it assumes a normal distribution. Secondly, the analysis focuses on the magnitude of differences between the measurements but does not consider the direction of the discrepancies and assumes that the agreement between the measurements is constant across the range of values, when in fact it may vary depending on the magnitude. Lastly, the method is limited to continuous data and may not be suitable for categorical or ordinal measurements, as well as it is not designed for the comparison of more than two measurements.

2.8 Literature review overview

There is a gap in the literature regarding the lack of a comprehensive evaluation of the various weighting methods used to calculate flow efficiency. Previous research has not thoroughly examined and compared different weighting approaches, hindering the development of a standardized and reliable methodology for assessing flow efficiency.

Also, there is a reduced understanding of the limitations and shortcomings associated with some of the existing weighting methods. Existing research fails to provide a comprehensive evaluation of the different weighting methods.

This work seeks to address this gap by exploring the available literature on weighting methods, evaluation frameworks and their application.

Table 2.1: Comparison of the areas addressed by former researches with the ones targeted by this work.

		Nienhaus (2004)	Näf (2015)	Klein (2021)	Parlak and Pescalli (2023)	Sieben (2023)	This Work
Review Areas	Supply Chain Management				•	•	•
	Efficiency Measures Consistency Conditions					•	•
	Value Curves				•	•	•
	Flow Efficiency Calculation	○	○	•	•	•	•
Design Areas	Novel Flow Efficiency Calculation Methods	•	•			•	•
	Statistical Analysis of Flow Efficiency Calculation Methods			•		•	•
	Criteria for Flow Efficiency Calculation Methods					•	•

Chapter 3

Problem description

By quantitatively evaluating the efficiency of the value chain through value curve analysis, businesses can identify areas for optimization and ensure that their supply chain activities are effectively aligned with customer needs and preferences, and thus create value in the most efficient way, enhance customer satisfaction, gain a competitive advantage, and drive long-term success.

Hilti has identified the need for a comprehensive overview of its products' supply chain in order to define enhancement strategies, despite the fact of centrally managing its supply chain. However, there was a vast amount of recorded data stored in the company's ERP system with a huge potential of contributing to improvement initiatives that the company was not taking advantage of.

The information available allowed to define the value curves for a significant percentage of the products sold by Hilti worldwide. Plotting these value curves would represent a significant benefit as it would increase their awareness of the most important steps in the value chain of a given product. However, by going one step further and finding quantitative metrics to define the flow efficiency of a given product, the impact of the project can be extended to many other stakeholders that would have a structured and scientifically based overview of their products' efficiency.

Notwithstanding the benefits of this work, there were four main challenges that needed to be address to make this initiative a success, which were:

i. Make the untapped data of product portfolios easily available.

ii. Calculate the flow efficiency for these products.

iii. Evaluate the performance of different flow efficiency calculation techniques.

iv. Understand which one is the best and most suitable according to the specificities of Hilti's products.

3.1 Company overview

Hilti provides products, systems, and services to the building and energy sectors worldwide. The company operates in over 120 countries and has more than 32,000 team members around the

world. It has production facilities in Europe (Liechtenstein, Austria, Germany, Hungary, and Norway), Asia (China, India, Malaysia and Taiwan), and North America (Mexico and USA).

Hilti was founded in 1941 by Martin Hilti and his brother Eugen in Schaan, Liechtenstein and nowadays is still a family-owned company, since all shares are owned by the Martin Hilti Family Fund. The business advocates for quality, innovation, and close customer relationships.

Hilti sales totaled more than CHF 6.3 billion in 2022 (Hilti, 2023) and uses a direct sales model in which approximately 25,000 of its employees deal directly with customers. More than 10000 products are included in the product portfolio, and 60 new product families are introduced each year.

Figure 3.1 shows the Sourcing Excellence department (DOS) and the supporting role it has across business units (BUs). Each BU is independent and accountable for its own performance and DOS provides them valuable support in the procurement process, globally, by improving and digitalizating their processes.

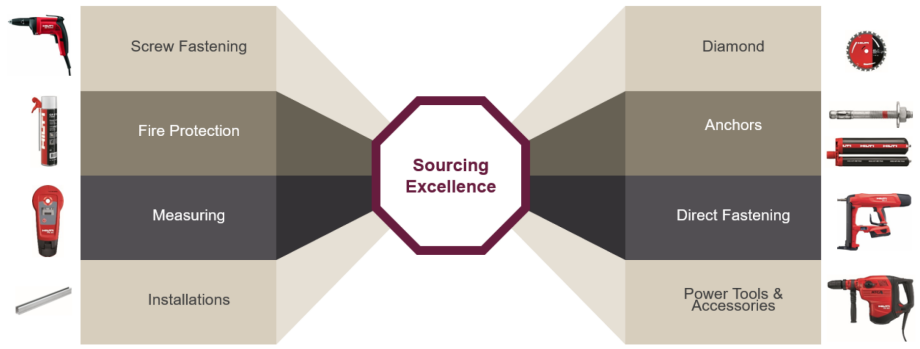


Figure 3.1: DOS as overarching cross-BU department to facilitate procurement process. Source: Hilti

This positioning gives the department a high level of expertise in supply chain management, considering the diversity of business practices with which it interacted. In addition, it also had the necessary leverage to perform substantive changes with significant impact across the company.

3.2 Data availability

In the past few years, Hilti has been adopting a global approach to its procurement process and, more broadly, to its supply chain. Contributing to this effort, the global deployment of an ERP package meant to cover all day-to-day operations of the enterprise. This solution is completed with a database that stores all the information and makes it available to everyone with the required access across the company.

For this project, the information about the production steps was available and easily accessible. However, time and value information regarding other supply chain steps like raw materials purchase values and transit times was hardly available and could only be collected through contact with the responsible people in each business unit and plant.

Despite the information being available in databases, another major challenge was the data quality and availability. Several challenges are identified and must be overcomed:

- **Data consistency**: the definition of production steps varies according to the business unit to which the item under analysis belonged and also varied within the team according to the person who entered the information into the system. This variability meant that certain activities might be considered, in some cases, different production operations while in others they are not.

- **Incomplete information**: in some cases, the existing information is not complete and makes the process mapping more complex. For example, some steps of the production process did not have an assigned time, making it impossible to perform the necessary calculations to process the data and therefore made impossible the analysis of the product in question.

- **Diversity of data**: given the size of Hilti's portfolio, there is an enormous diversity of production processes. This requires data collection models that are flexible enough to accommodate all possible variations and error detection mechanisms that guarantee the quality and standardization of the information extracted.

- **Available tools**: SAP did not allow the mass collection of information regarding the production process for a wide range of items. Thus, a significant amount of manual work was required and could have undermined any analysis scalability.

3.3 Calculation methods evaluation

Managing capital deployment and focusing on important inventory and working capital problems was significantly more difficult due to the lack of a valid and widely accepted flow efficiency calculation method. The use of scientifically based decision-making processes was undermined by the absence of a structured approach, with the existing models producing results that were both unpredictable and possibly deceptive. Due to this, improvements in operational performance were hampered, which also wasted resources and caused efforts to be misdirected.

Extensive testing in large-scale settings had not been done on the current flow efficiency calculation techniques. Given the lack of assessment of the robustness and accuracy of these methods, the selection process was also more difficult. With this, the BUs lacked a clear understanding of which method was best suited for their unique product characteristics and value curves because the applicability and transferability of these methods were still unclear.

3.4 Summary of challenges

First and foremost, it was essential to improve the quantity and diversity of data used to calculate flow efficiency. By easing the process of having this data available, it was easier for the stakeholders to have an understanding of what was happening with their products within the production lines.

Secondly, it was critical to propose novel calculation strategies that worked around the limitations of the existing ones. By creating robust and adaptable methods that could provide more precise insights into flow efficiency, businesses can pinpoint important areas for improvement and allocate resources more effectively.

Lastly, creating new methods is not enough if testing and evaluation of flow efficiency calculation methods is not performed. The criteria defined in Sieben (2023) evaluation framework needed to be put into practice to assess the novel and existing weighting methods. To understand how well these methods perform in various scenarios, a large, diverse, and representative product portfolio must be tested.

Chapter 4

Methodology

This chapter describes how the issues identified above have been addressed. Thus, each section will describe the methodology used to respond to each of the challenges, starting with data collection, processing and analysis. Then, the criteria used to evaluate each flow efficiency calculation method are described and, finally, an analysis to determine the method to be used for the different use cases is presented.

This work used Cross-Industry Standard Process for Data Mining (CRISP-DM) as a guide for data mining and analytics. This methodology provides a structured and flexible framework that can be adapted to different goals, allowing organizations to systematically and effectively address their data analytics needs (Wirth and Hipp, 2000).

The CRISP-DM process consists of six major phases and Figure 4.1 shows how this stages are related (Wirth and Hipp, 2000).

i. **Business Understanding:** In this phase, the project objectives and requirements are defined. The focus is on understanding the business goals, assessing the situation, and formulating the data mining problem.

ii. **Data Understanding:** This phase involves data collection and exploration. It includes activities such as identifying the data sources, acquiring the data, and performing initial data exploration to understand the structure, quality, and relationships within the data.

iii. **Data Preparation:** In this phase, the data is cleaned, transformed, and prepared for analysis. This includes activities such as data cleaning, integration, transformation, and feature engineering, in order to ensure that the data is suitable for modeling.

iv. **Modeling:** This phase involves the selection and application of appropriate modeling techniques to build predictive or descriptive models. It includes activities such as selecting the modeling techniques, building the models, and evaluating their performance.

v. **Evaluation:** In this phase, the models are evaluated to assess their quality and effectiveness in addressing the business objectives. The models are validated against the evaluation

criteria defined in the business understanding phase. If the models do not meet the desired criteria, the previous phases may need to be revisited.

vi. **Deployment:** The final phase involves deploying the data mining solution into the production environment. This includes activities such as integrating the models into business processes, creating user interfaces, and providing training and documentation for end-users. Maintenance and monitoring procedures are also established to ensure the continued effectiveness of the solution.

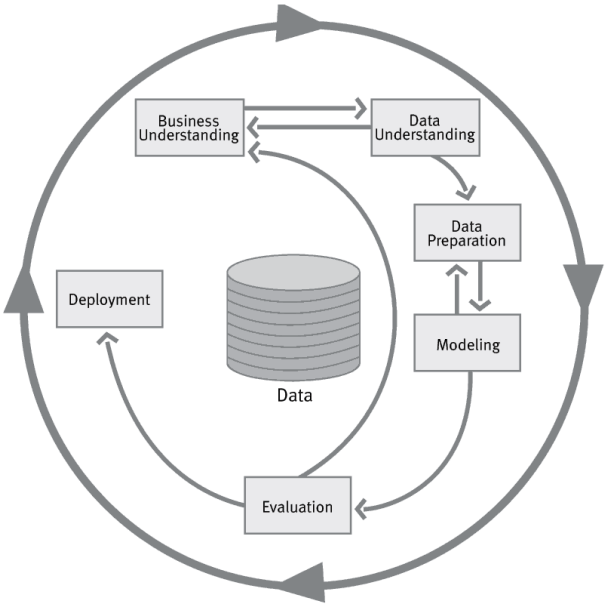


Figure 4.1: The six phases of the CRISP-DM Process Model for Data Mining and the relationship between them (Wirth and Hipp, 2000)

4.1 Business Understanding

A detailed explanation of the project objectives and requirements from a business perspective was provided in Chapter 3.

4.2 Data Understanding

To ensure a comprehensive understanding of the data and gather key information for the data preparation stage, interviews were conducted with unit managers, project managers and the Head of Digital and Operational Excellence, who are responsible for managing the production of a portfolio of products and for the innovation at one of the Hilti Group's factories. These interviews aimed to evaluate data quality before the data preparation process and to engage the stakeholders from the start.

Firstly, the willingness of the involved people to adopt the proposed method was assessed to ensure the successful implementation and acceptance of the developed approach.

Secondly, discussions centered around data quality, including its timeliness, reliability, and any potential constraints or issues that might impact the accuracy and usability of the data. Furthermore, the interviews provided valuable insights into the specific product portfolio represented in the data. This qualitative assessment of the product portfolio proved to be useful at a latter stage of the analysis.

Lastly, a guided tour of the plant was conducted to enhance understanding of the operational activities being carried out.

Given the aim of creating a scalable methodology that would work not only for these item numbers, but for any amount of items under analysis, the author had to rely in information that is updated frequently, to ensure the information timeliness, and that is entered based on a clear and well-publicized process across the organization, to guarantee the information comparability.

Although there were several sources of information that could be used, the only one that met these two criteria was transaction CK13N in SAP. With this transaction, that was used across all plants of the Hilti Group, it was possible to obtain the full report of the processes required to obtain the finished goods, including duration and cost, as well as the raw materials and components related to them, divided in production steps as shown in Figure 4.2.

Item Number	Item Category	Resource	Resource (Text)	Origin Group	Total Value	Crcy	Quantity	Output Unit of Measure	Supplier	Purchasing info rec.	Costing Date (Key)
25	G	519351 941000	Production OH Adm. %	M1WD	-	CHF		-			
26	G	519351 942000	Production OH Prod.	M1WD	-	CHF		-			
27	G	519351 940000	Material Overhead %	O1WD	-	CHF		-			
28	G	519351 940000	Material Overhead %	M1WD	-	CHF		-			
Operation					-	CHF					
1	E	511670 167001 2200	KALTPRESSEN		-	CHF		- H			
2	E	511670 167001 2000	KALTPRESSEN		-	CHF		- H			
3	E	511670 167001 2100	KALTPRESSEN		-	CHF		- H			
4	M	0501 2084021	Granulate HC	M1WD	-	CHF		- KG			1/1/2023
5	M	0501 2314815	Granulate FeNiX	M1WD	-	CHF		- KG			1/1/2023
6	M	0501 2088091	Cont. DIA SMSHCTI	O1WD	-	CHF		- KG	1077987	5300570883	1/1/2023
Operation 0010					-	CHF					
7	E	511644 164404 2200	SEGMENT EINLEGEN		-	CHF		- H			
8	E	511644 164404 2000	SEGMENT EINLEGEN		-	CHF		- H			
9	E	511644 164404 2100	SEGMENT EINLEGEN		-	CHF		- H			
Operation 0020					-	CHF					
10	E	511643 164302 2200	HEISSPRESSEN		-	CHF		- MIN			
11	E	511643 164302 2000	HEISSPRESSEN		-	CHF		- H			
12	E	511643 164302 2100	HEISSPRESSEN		-	CHF		- H			
Operation 0030					-	CHF					
13	E	511659 165901 2200	SANDSTRAHLEN		-	CHF		- H			
14	E	511659 165901 2000	SANDSTRAHLEN		-	CHF		- H			
15	E	511659 165901 2100	SANDSTRAHLEN		-	CHF		- H			
Operation 0040					-	CHF					
16	E	511649 164906 2200	SEGMENT SCHÄRFEN		-	CHF		- MIN			
17	E	511649 164906 2000	SEGMENT SCHÄRFEN		-	CHF		- H			
18	E	511649 164906 2100	SEGMENT SCHÄRFEN		-	CHF		- H			
Operation 0050					-	CHF					
19	E	511676 167602 2200	Qualitätsprüfung Segmente		-	CHF		- H			
20	E	511676 167602 2000	Qualitätsprüfung Segmente		-	CHF		- H			
21	E	511676 167602 2100	Qualitätsprüfung Segmente		-	CHF		- H			
Operation 0060					-	CHF					
22	E	511676 167601 2200	VERPACKEN		-	CHF		- H			
23	E	511676 167601 2000	VERPACKEN		-	CHF		- H			
24	E	511676 167601 2100	VERPACKEN		-	CHF		- H			
Operation 0070					-	CHF					
					-	CHF					

Figure 4.2: Example of the data available through SAP transaction CK13N showing the steps of the production process and the assigned value an time, that were hidden due to confidentiality.

However, there were two major drawbacks of this approach: it ignores all the supply chain steps after the manufacturing and assembly in the plant and requires running the transaction for each item individually. Despite this fact, the existing information could be used as a reliable proxy to assess overall efficiency.

Other limitations related to data consistency were identified during the data collection process. Despite the widespread dissemination of good practices for updating information, the way it was described varied between functional units, namely:

- **Step definition** - the number of tasks, their complexity and the times between steps are important variables that help define a step, however these were considered arbitrarily depending on the user responsible for updating the information.

- **Time allocation** - in the collected information, there are value-added steps with no time allocation, which, for the problem under analysis, would mean infinite efficiency.

In the context of this study, data was collected from two distinct product portfolios manufactured at the same plant located in Schaan, Liechtenstein, which the primarily focus is on producing performance-critical components. The portfolio one comprises 484 item numbers, which are specifically categorized under the Diamond BU, items that are designed for utilization in saw blades intended for cutting concrete and other mineral materials. Additionally, the portfolio two consists of 605 products that are part of Hilti's anchors product portfolio.

4.3 Data Preparation

The data preparation activites ranged from getting the data from the SAP transaction and exporting it to Excel, to the data cleaning and transformation tasks done in Matlab. These activities can be summarized into three major stages described in the following sections.

4.3.1 Extraction

The data extraction process is a critical component of the data preparation stage since it served as the foundation for the subsequent stages of this study. The data to be analyzed was stored in Hilti's ERP and it was curated and updated by Hilti's Unit Managers, who were responsible for managing product portfolios within specific production plants.

After having a clear understanding of the data sources, their limitations, and the requirements for successful implementation, the Unit Managers provided a list of item numbers to be analyzed. Leveraging this information, individual tables with essential data, were extracted from SAP, capturing activity descriptions, component costs, and task durations. To ensure organization and manageability, the extracted tables were saved as individual Excel workbooks, each uniquely identified by the corresponding item number, ensuring data traceability and enabling efficient data retrieval and manipulation during subsequent stages of the analysis.

From the 484 item numbers in portfolio one, only 334 had information stored in SAP, mainly due to products in the introduction or phase-out stages. Regarding portfolio two, the 605 items had up-to-date information in SAP.

4.3.2 Cleaning and Transformation

After the data was extracted, it underwent a series of cleaning and transformation steps to ensure consistency and quality. Due to the varying table formats in SAP, which depended on the number of operations and tasks within a production process, the initial step involved standardizing the extracted data. It was necessary to transform the data into a unified table structure where values for each step are consistently located. To achieve this VBA code was used, facilitating the retrieval of information from the original documents and populating a standardized table format in a single Excel workbook, with information from different product portfolios. The code employed was designed to be flexible and robust, capable of accommodating diverse input variations while minimizing sensitivity to incorrect inputs.

The standardized table format served as a template sheet that had several data validation mechanisms to ensure data quality. It automatically calculated the time and value of each operation, generated the corresponding value curve, and incorporated data validation checks for factors such as the number of operations, tasks per operation, accumulated value calculation, and identification of operations without assigned time. After this step, observations that don't have a time or value assigned to each and every single operation are automatically excluded. Additionally, as data regarding overhead costs was provided at the item number level, these costs were distributed based on the duration of each operation.

Following the completion of the data cleaning and standardization process in Excel, the transformed tables are loaded into Matlab for further cleaning. In this stage, the data was stored according to the appropriate data structures required for the subsequent calculations. Then, to ensure the integrity of the data, duplicates are identified and addressed to prevent any biases in the analysis. In adittion, outlier detection techniques are applied to identify and exclude data points that deviate significantly from the expected patterns, for this scatter plots are generated, both with the original values and after applying min-max feature scaling, enabling visual identification.

At this stage, eight line items were removed from portfolio one due to lack of information available, namely steps without time or value assignment. However, almost 90% of portfolio two items undergo external operations for which no relevant information was available. Consequently, it was not feasible to construct value curves for these products, leading to their exclusion from the analysis and resulting in a final amount of 64 observations for portfolio two.

The merger of the datasets from both portfolios, resulted in a compilation of 390 observations. These observations exhibited a significant degree of heterogeneity, with final values ranging from CHF 108 to CHF 53,230. The observed durations of these items span a range of 2 minutes to 110 hours, and the number of process steps involved varied between one and seven. A scatter plot, with min-max scaling applied to each value curve due to confidentiality, is presented in Figure 4.3 and effectively illustrates the aforementioned characteristics.

With this process, data integrity and consistency are maintained, contributing to accurate further calculations of flow efficiency and reducing the impact of low-quality data on the final results.

The data contained within the SAP system was confined to the production stages associated

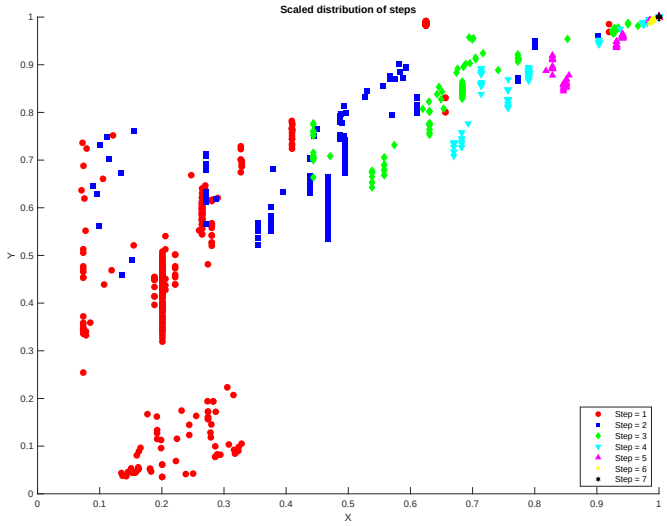


Figure 4.3: Scaled distribution of value curves' points across the dataset. Overall, the dataset showed similar distribution patterns for different item numbers. Source: The author

with each item, thereby it was used as a substitute for comprehending the broader supply chain. The production steps, encompassing their temporal duration and value contribution, were utilized as an approximation for the overall chain dynamics. Despite this restricted scope, the underlying principles remain consistent, as it was the movement of goods that was being fundamentally examined. Consequently, it remained valid to perform flow efficiency calculations, since the evaluation of each method's performance given a value curve was not compromised, although the disparity lied in the level of detail involved in the analyzed process.

4.4 Modeling

The modeling phase was slightly adapted from the original CRISP-DM model, since this project did not address a pure data mining problem. Thus, the usual model-building process that would have taken place at this stage was adapted to the coding and application of the existing flow efficiency calculation methods to the created value curves.

Different variations of the methods were created, depending on their characteristics. For models following a total value approach, it was possible to create versions that combine the initial model with weighting approaches from other calculation methods. Also, there are models to which min-max scaling was applied, and others where the original values were used and, for the models involving linear regression, the z-standardization was also considered as a variation of the original method. All the methods, their variations and their respective description are presented in Table 5.1.

4.5 Evaluation

According to Sieben (2023) evaluation framework, several steps must be followed to evaluate the performance of value efficiency calculation methods. This framework to compare all the methods encompassed a set of minimum criteria that each model must fulfil and suggested the usage of metrics such as Spearman's coefficient and Bland-Altman analysis to assess the consistency conditions that efficiency calculation methods must fulfill. This framework was followed and the steps used to conduct are described in the following sections.

4.5.1 Bland-Altman plot analysis

Firstly, each of the developed calculation models described before was applied to the value curves dataset under investigation. Once the flow efficiency values for each method are obtained, a quantitative assessment of the level of agreement was be done by computing important summary statistics, including the regression coefficient, the R^2 and the coefficient of reproducibility (RPC). These statistics offered objective measures on how closely the flow efficiency numbers obtained using the various calculation techniques agree with one another and shed light on the accuracy, comparability, and presence of any potential outliers or notable differences among the methods.

The Nienhaus model was regarded as a benchmark calculation technique and served as a reference point for assessing the performance of the other models since it was the most acknowledge method in the literature and considering its robustness and reliability for a large spectrum of value curve configurations. This observation is particularly valid within the dataset under analysis, where efficiencies reach a maximum of 33% when employing the Nienhaus model, as the primary drawback identified for this method lies in the high-efficiency value curves.

For the most prominent methods, the power of the Bland-Altman plot was leveraged to graphically represent the differences in the flow efficiency values obtained from the different calculation techniques Klein (2023). A comprehensive view of the overall degree of agreement or disagreement was possible thanks to this plot.

4.5.2 Spearman's rank correlation coefficient

The Spearman's coefficient to compare rankings of a value curve calculated by one method with rankings obtained from another and to assess the consistency and directionality of the relationships between the methods, determining whether they exhibit a monotonic increasing or monotonic decreasing pattern. With this, it was possible to quantitatively measure the similarity or dissimilarity between the flow efficiency figures derived from the different methods. Here, for the same reasons stated in Section 4.5.2, also Nienhaus calculation method will be used as a benchmark.

To calculate the Spearman's correlation coefficient, pre-existing code available in MATLAB Central File Exchange was used (Leontitsis, 2023). This function allows the calculation of the Spearman coefficient from 2 or more datasets, and the associated t-test and p-values. The datasets

to be compared were the arrays with the calculated flow efficiency based on the different methods previously described.

The Spearman's coefficient was employed as a preliminary analysis to assess extreme cases, as a significant coefficient can only be achieved when there is concordance between the top and bottom performers across various methods.

4.5.3 Criteria to evaluate an efficiency calculation method

The first criteria of statistical equivalency may be evaluated using Bland-Altman analysis, which is acknowledge by the suitability for analyzing agreement and consistency between two measurement methods or procedures. It clearly illustrates the degree of agreement between efficiency estimates produced from different methods versus their mean and enables a statistical study of any systemic biases. This investigation sheds light on the statistical equivalent of efficiency estimates, an important consideration for accurate comparisons and reliable conclusions.

On the other hand, the Spearman coefficient assesses the consistency and correlation of ranks by quantifying the strength and direction of the monotonic relationship between rankings and it is, therefore, appropriate for evaluating the second requirement of similar ranks. As an objective measurement of the degree of correlation and consistency in rankings produced by different methodologies, it enables the assessment of the extent to which rankings are comparable.

In addition, the third condition states that the size of differences and whether the same entities are consistently classified as top and worst performers across methodologies have particular relevance. Although it might not be captured directly by the Spearman coefficient, it is already a good proxy to which a visual inspection of the linear regression to check for the highest and lowest values was added, understanding where they position themselves relative to the others.

4.5.4 Minimum criteria

Lastly, as suggested in Sieben (2023) evaluation framework, the fulfilment of the minimum criteria for each one of the models was done. The defined criteria are described in the following sections.

4.5.4.1 Mirror condition

The mirror condition states that it is mandatory to get different total efficiency values for two value curves that differ from each other by a horizontal followed by a vertical mirroring (or vice-versa), regardless of the weighting method used.

Figure 4.4 shows the mirror condition for the simplest case of a two-steps value curve that differ from each other by a horizontal followed by a vertical mirroring. Using the simple average of the partial flow efficiencies results in the same overall efficiency, however the two processes have completely different total flow efficiencies. This explains, in part, the importance of weighting methods that consider the stage at which a certain step takes place.

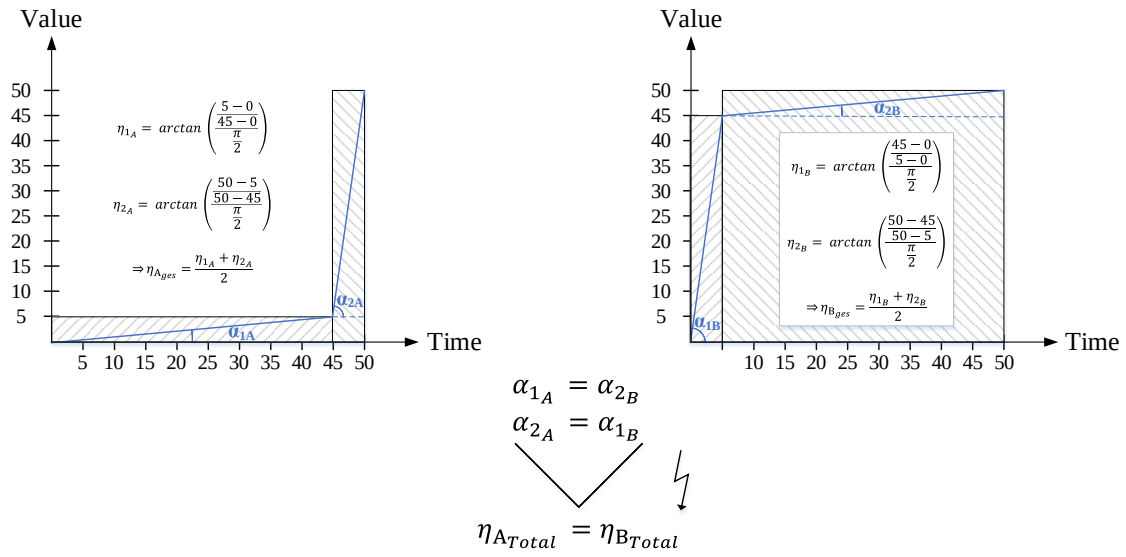


Figure 4.4: Comparison of two scenarios using the simple average of the partial flow efficiency. Source: The author and Sieben (2023)

4.5.4.2 Time increment condition

As pointed out by Näf (2015), Nienhaus model leads to an unintended increase in the flow efficiency for steps with a high lead time compared to their value. Sieben (2023) turned this into a condition which states that, ceteris paribus, an increase in time for the first step of a value curve does not correspond to an increase in the overall flow efficiency.

This time increment condition is relevant to the industrial practice and Figure 4.5 shows an example of what is the common shape of the value curves where this condition should be considered.

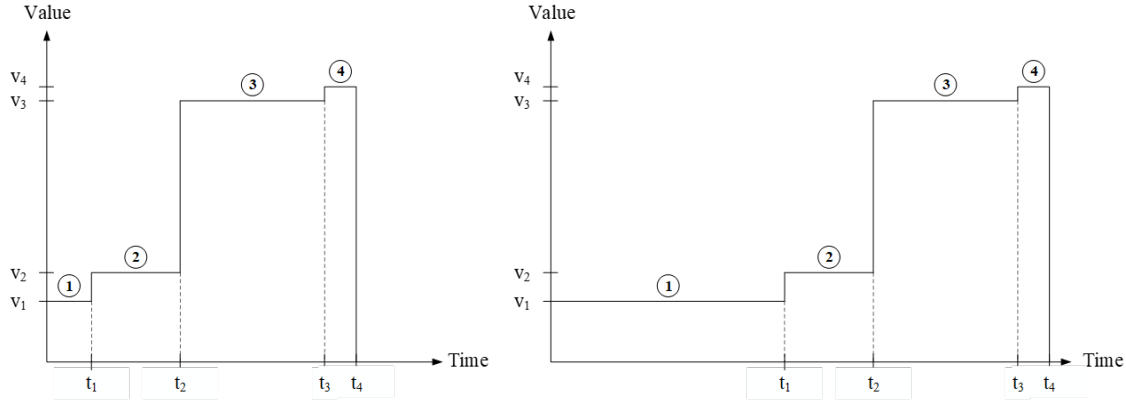


Figure 4.5: Comparison between a "normal" value curve and other with a time increment in the first step. Source: The author and Sieben (2023)

4.5.4.3 Value decrement condition

In industrial practice, it cannot be ruled out that the accumulated value is reduced from one step to the next one. This may happen due to obsolescence, spoilage or damage and means a reduction in the total accounting value, thus, the value per item may be lower than at the end of the previous step (Sieben, 2023).

Therefore, the third condition states that the weighting method must be able to represent such value decrements and the total flow efficiency must always be lower than without the negative value step. Figure 4.6 compares the value curve of a normal supply chain with the value curve of a supply chain where step 2 is a value decrement step. Applying Nienhaus' method to this scenario would return a higher flow efficiency for the value decrement scenario, which should not be the case given that value is being destroyed.

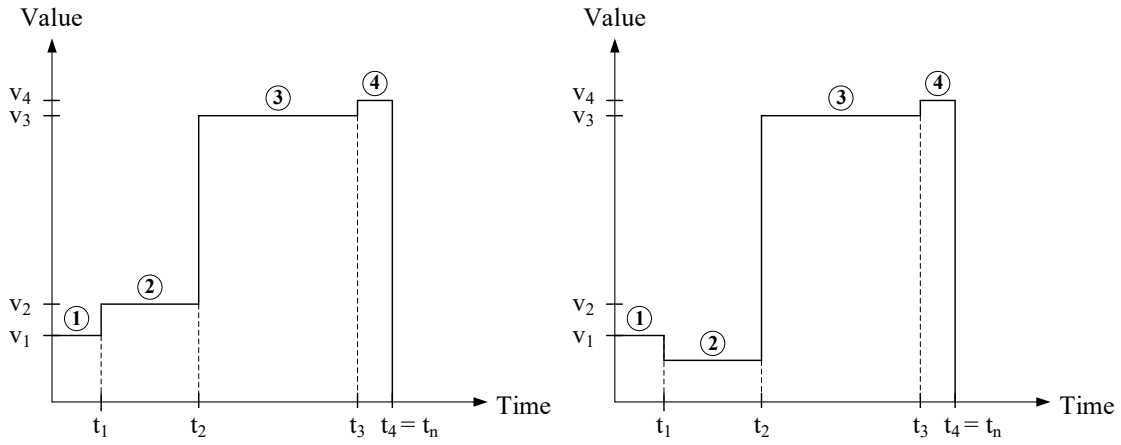


Figure 4.6: Comparison between a "normal" value curve and other with a value decrement in the second step. Source: The author and Sieben (2023)

4.6 Deployment

The practical implementation of the defined calculation method for flow efficiency constitutes the projection of the deployment phase of the CRISP-DM process for this project. However, as of the publication date of this work, there has been no practical implementation of the results obtained.

Chapter 5

Results

This chapter describes the outcomes of the evaluation of different flow efficiency calculation methods within the scope of Hilti's supply chain. Firstly, a flow efficiency calculation approach created during this work, named Weighted Angle Total Value, is presented. Secondly, different flow efficiency calculation methods were compared using Sieben (2023) evaluation framework. Lastly, conclusions regarding which are the best performing are drawn.

A bespoken nomenclature was devised to help the discussion of the findings. This nomenclature, as outlined in Table 5.1, assigned a personalized designation to each of the methods present in the literature and its variations. The designation consists of the letter "M" followed by a number representing the respective method which is accompanied by different calculation indicators: "W" denotes that a weighting approach was used, with the specific type of weighting method in the description, "A" indicates it was adapted, "S" shows that min-max scaling was performed, and "ST" represents that z-standardization was applied to the initial data. Finally, "Total Value" methods[1] are also distinguished from "Partial Efficiency" ones by adding "Total Value" to the description of the methods that follow that approach.

Table 5.1: Nomenclature for all the methods under analysis.

Model	Description	Model	Description
M1	Nienhaus Surface Total Value	M10s	Exponential Weighting (scaled)
M2	Naef Surface Total Value	M11	Gravitational Distance Weighting
M3	Simple Aggregation	M11w	Gravitational Distance Weighting (weighted with M6s)
M3s	Simple Aggregation (scaled)	M11st	Gravitational Distance Weighting (Z-Standard)
M4s	Value Based Weighting (scaled)	M11wst	Gravitational Distance Weighting (both Z-Standard and M6s weighting)
M4as	Value Based Weighting (adapted and scaled)	M12	Gravitational Distance Total Value
M5s	Time Based Weighting (scaled)	M12w	Gravitational Distance Total Value (weighted with M6s)
M6s	Combined Value Time Based Weighting (scaled)	M12st	Gravitational Distance Total Value (Z-Standard)
M7s	Value Vector Based Weighting (scaled)	M12wst	Gravitational Distance Total Value (both Z-Standard and M6s weighting)
M7as	Value Vector Based Weighting (adapted and scaled)	M13	Regressive Gravitational Distance Total Value
M8s	Horizontal Slack Based Weighting (scaled)	M13st	Regressive Gravitational Distance Total Value (Z-Standard)
M9s	Vertical Slack Based Weighting	M14	Weighted Angle Total Value

[1]Total value as defined by Sieben (2023) refers to models that consider the all value curve configuration rather than focusing on individual steps.

5.1 Weighted angle total value

After understanding the main drawbacks of the existing approaches, the author decided to create a complementary approach to flow efficiency calculation that was added to the list of methods under analysis.

The Weighted Angle Total Value method, belonging to the Total Value category, focuses on incorporating steps that have the highest impact on overall efficiency. For each step but the last one, two angles are determined: firstly, the angle α_i is calculated between the x-axis and the line connecting the origin $(0,0)$ to the endpoint of that step (t_i, v_i); secondly, the angle γ_i is calculated between the x-axis and the line formed by connecting the endpoint of the step (t_i, v_i) to the endpoint of the value curve (t_n, v_n).

Subsequently, the step with the smallest difference between α_i and γ_i is identified, indicating the step at which the average efficiency up to that point in time t_i is the lowest compared to average efficiency of the subsequent steps until the end of the process.

Finally, the two average efficiencies, α_i and γ_i, are utilized in calculating the overall process efficiency using a weighting approach based on a quadratic function. Specifically, t_i^2 is employed as the weight for the average efficiency until step i, while $(t_n^2 - t_i^2)$ serves as the weight for the average efficiency from step i until the end of the process.

Figure 5.1 shows the determination of α_i and γ_i for the first step of the value curve. The figure is only intended to illustrate the identification of angles for the first step and is repeated for all steps except the last one, followed by the calculation of the difference between the angles.

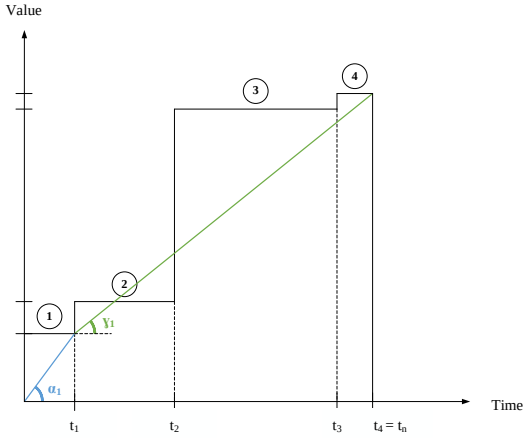


Figure 5.1: Representation of Weighted Angle Total Value. Source: The author and Sieben (2023)

Once the step i, corresponding to the $\min(\alpha_i - \gamma_i)$, has been determined, the calculation of the overall efficiency is performed, incorporating the quadratic weighting, using Equation 5.1:

$$\eta = \frac{\frac{2\cdot\alpha_i}{\pi}\cdot t_i^2 + \frac{2\cdot\gamma_i}{\pi}\cdot(t_n^2 - t_i^2)}{t_n^2} \tag{5.1}$$

5.2 Consistency conditions fulfilment

As described in Section 4.5.2 and 4.5.1, Spearman coefficient and Bland & Altman plots were used to better understand the relation between different calculation methods and to provide objective measures to evaluate the compliance of the proposed methods with the consistency conditions defined by Bauer et al. (1998) for efficiency measurement methods, as proposed by Sieben (2023)'s evaluation framework.

5.2.1 Comparable means, standard deviations and other properties

Following the data collection and preparation process outlined in Section 4.3, all the methods described in this study were employed to calculate the flow efficiency for each observation[2]. This computation was executed using a Matlab script, an extension of the previous work conducted by Parlak and Pescalli (2023). The resulting flow efficiency values were subsequently stored in a table for further analysis, encompassing comparisons and the calculation of general statistical metrics such as the average, standard deviation, and mean absolute difference between each pair of models.

Upon conducting this initial analysis and according to the consistency condition (i), which states that the efficiency scores generated by different approaches should have comparable means, standard deviations and other distributional properties, the performance of certain methods fell significantly below expectations, as inferred from the low variance and extreme averages observed in such an heterogeneous dataset. Notably, ten methods exhibited subpar performance, as illustrated in Table 5.2.

For the remaining ones, the results of the mean absolute deviation against the Nienhaus method are shown in Table 5.3. This was only used for reference since no action was taken based on that information given that it is a comparison against a faulty method.

Then, Bland & Altman plots were created for all the possible combinations of two different methods, 252 in total, both using Gaussian and non-parametric statistics. Based on this, the fulfilment of the criteria (i), regarding the generation of comparable means, standard deviations and other distributional properties by different approaches, was assessed. Only statistical results such as the regression coefficient (β), the r-squared (R^2) and the reproducibility coefficient (RPC) were analysed based on the figures shown in Appendix A.

This analysis, confirmed some of the takeaways previously drawn, but was also useful to get new insights both regarding under-performing methods and other methods which show potential to be selected as the go-to method.

Regarding the regression coefficient, it is a good indicator of how the flow efficiency distributes across the range of possible efficiency values for each model and, from the models still in analysis, M2, M3s, M9s, M10s, M12st and M14 were within and acceptable range compared with M1 - greater than 0.45 and lower than 1.

[2]Sieben et al. (2023) refers to "item-line combination" since a specific product might be produced in two or more production lines, in which case the items need to be analysed seperately.

Table 5.2: Average and standard deviation for each model - based on the data understanding, M3, M5s, M6s, M7s, M7As, M11wst, M12w, M13, M13st showed statistical propertie that are not aligned with what was expected (highlighted in red).

Model	Average	Standard Deviation
M1	0.18	0.10
M2	0.16	0.10
M3	**0.99**	0.00
M3s	0.39	0.05
M4s	0.57	0.04
M4As	0.55	0.08
M5s	0.44	0.04
M6s	0.44	0.04
M7s	**1.00**	0.00
M7As	**0.01**	0.45
M8s	0.60	0.14
M9s	0.31	0.15
M10s	0.31	0.15
M11	0.35	0.08
M11st	0.20	0.14
M11w	0.10	0.09
M11wst	**0.05**	0.06
M12	0.61	0.05
M12w	0.52	0.02
M12st	0.59	0.06
M12wst	0.49	0.02
M13	**0.08**	0.06
M13st	**-0.47**	0.16
M14	0.43	0.13

Table 5.3: Mean Absolute Deviation of remaining models to Nienhaus - only used as a reference since Nienhaus was recognized as a faulty method.

Model	Mean Absolute Deviation to Nienhaus
M2	6%
M11st	54%
M10s	98%
M9s	103%
M11w	334%
M11	558%
M14	618%
M3s	724%
M12st	1161%
M12	1260%
M4As	1367%
M4s	1378%
M8s	1428%

For the R^2, M3s, M4As, M8s, M11, M11w and M12 performed poorly against Nienhaus, with values below 0.40, suggesting that the methods are not consistent with M1 and that there is limited correlation between the results.

Lastly, the RPC values for all the methods under analysis are below 0.40, with M2 and M14 outperforming the remaining models.

5.2.2 Similar rankings across methods

Bauer et al. (1998) also describes two conditions that are mainly related with the way the different calculation methods rank the observations. Condition (ii) highlights how different approaches should rank the observations in the approximately the same order and Spearman coefficient addresses exactly this relation between the output of different methods, where a higher Spearman coefficient meaning a closer match between the ranks of two different methods. Table 5.4 shows the Spearman coefficient for the methods still under analysis, for any combination of flow efficiency calculation methods refer to the Appendix A. For example, M10s ranked the observations in a very similar way to the method M11. When comparing against Nienhaus, M9s and M10s seemed to perform well, however it is important to consider that a better performing method will show divergences against this method given the time increment condition flaw.

Moreover, from the low performance side, methods M4s, M4As and M8s show an inverted ranking in comparison to the remaining ones. These methods shall be removed from further analysis as they don't fulfill the condition under analysis.

Table 5.4: Spearman's coefficient between methods - M4s, M4As and M8s show a negative monotonic relationship to Nienhaus, suggesting that they are not capturing the efficiency variation correctly.

	M1	M2	M3s	M4s	M4As	M8s	M9s	M10s	M11	M11st	M11w	M12	M12st	M14
M1	1.00													
M2	0.79	1.00												
M3s	0.57	0.58	1.00											
M4s	-0.64	-0.53	-0.71	1.00										
M4As	-0.41	-0.33	-0.23	0.61	1.00									
M8s	-0.45	-0.19	-0.31	0.64	0.52	1.00								
M9s	0.73	0.45	0.73	-0.90	-0.46	-0.58	1.00							
M10s	0.73	0.45	0.65	-0.71	-0.67	-0.53	0.81	1.00						
M11	0.53	0.34	0.76	-0.50	-0.46	-0.27	0.63	0.87	1.00					
M11st	0.59	0.46	0.46	-0.30	-0.38	-0.05	0.44	0.71	0.73	1.00				
M11w	-0.16	-0.36	0.06	-0.16	0.13	-0.55	0.19	-0.02	-0.07	-0.55	1.00			
M12	0.48	0.47	0.06	-0.40	-0.62	-0.10	0.29	0.33	0.10	0.40	-0.56	1.00		
M12st	0.42	0.52	-0.04	-0.22	-0.56	0.10	0.12	0.24	0.05	0.45	-0.72	0.93	1.00	
M14	0.51	0.24	0.21	-0.44	-0.52	-0.28	0.53	0.63	0.44	0.38	-0.02	0.20	0.19	1.00

5.2.3 Identification of extreme cases

For condition (iii), which states that different approaches should identify mostly the same observations as "best practice" and as "worst practice", Spearman's coefficient also works as a pre-analysis, since a high coefficient can only be obtained if there is a match between the best and

worst performers of different methods. In addition, the five ($\approx 1\%$) best and worst efficiency rates of each method were compared and the respective item number in order to assess how consistently the different methods elected the same items. The results, in Tables 5.5 and 5.6, show that there was more consistency in the low efficiency ranking than in the high efficiency. Here, the low efficiency values are the most relevant considering that Nienhaus performs particularly well under these circumstances, where M9s and M10s clearly stand out from the remaining ones.

Table 5.5: Items numbers by method for the five highest efficiency values - disperse ranking of item numbers.

Model	Higher Ranking:	#1	#2	#3	#4	#5
M1	**Item Number:**	2214784	2214785	2214786	2207530	2207531
	Efficiency Value:	0.33	0.32	0.32	0.31	0.31
M2	**Item Number:**	2214784	2214785	2214786	2207530	2207531
	Efficiency Value:	0.33	0.32	0.32	0.31	0.31
M3s	**Item Number:**	249448	249447	320798	320806	320805
	Efficiency Value:	0.63	0.62	0.57	0.53	0.52
M9s	**Item Number:**	2344913	2344914	2208064	2344912	2344911
	Efficiency Value:	0.59	0.59	0.59	0.59	0.59
M10s	**Item Number:**	2344913	2344914	2208064	2344912	2344911
	Efficiency Value:	0.59	0.59	0.59	0.59	0.59
M11	**Item Number:**	249448	249447	320798	302297	320806
	Efficiency Value:	0.75	0.74	0.67	0.60	0.60
M11st	**Item Number:**	2214988	2214784	2214785	2214786	2392286
	Efficiency Value:	0.50	0.46	0.46	0.46	0.45
M11w	**Item Number:**	2214988	2215163	2215133	2215165	2215365
	Efficiency Value:	0.40	0.37	0.34	0.34	0.33
M12	**Item Number:**	2060966	2060967	2243881	2243882	2141406
	Efficiency Value:	0.72	0.71	0.66	0.66	0.66
M12st	**Item Number:**	2243881	2243882	2141406	2141890	2141407
	Efficiency Value:	0.67	0.67	0.67	0.67	0.67
M14	**Item Number:**	2344914	2208064	2344913	2208063	2344912
	Efficiency Value:	0.55	0.55	0.55	0.55	0.55

In addition, the dispersion of the data points was observed against the regression line to check for different behaviours in the extremes cases - low or high efficiency - in order to assure the complete fulfilment of this condition. This analysis, the most time consuming one, was done only for the methods which show promising results for the previously done analysis. In Figure 5.2, the graphs comparing M1 with M9s and M10s are showed. The points highlighted in red were identified as causes of inconsistency and were therefore subject to a case-by-case analysis that will be described in Section 5.4.

5.3 Minimum criteria fulfilment

Finally, a comprehensive evaluation of all methods was conducted to assess their adherence to the predefined criteria outlined in Section 4.5.4.

Table 5.6: Items numbers by method for the five lowest efficiency values - M1, M9s and M10s classified the same item numbers as the least efficiency.

Model	Ranking:	#1	#2	#3	#4	#5
M1	**Item Number:**	2022172	2021883	2021736	2022173	2021734
	Efficiency Value:	0.01	0.01	0.01	0.01	0.01
M2	**Item Number:**	2208606	2208067	2208064	2208066	2022172
	Efficiency Value:	0.00	0.00	0.00	0.00	0.01
M3s	**Item Number:**	2206178	2207603	2278297	2167533	2206177
	Efficiency Value:	0.30	0.30	0.30	0.30	0.31
M9s	**Item Number:**	2022172	2021883	2021736	2022173	2021734
	Efficiency Value:	0.01	0.01	0.01	0.01	0.01
M10s	**Item Number:**	2022172	2021883	2021736	2022173	2021734
	Efficiency Value:	0.02	0.02	0.02	0.02	0.02
M11	**Item Number:**	2060967	2207603	2207602	2215408	2227871
	Efficiency Value:	0.14	0.21	0.23	0.23	0.23
M11st	**Item Number:**	2215130	2022172	2021883	2021736	2022173
	Efficiency Value:	0.01	0.01	0.01	0.01	0.01
M11w	**Item Number:**	300749	300750	2099486	300707	300751
	Efficiency Value:	0.04	0.04	0.04	0.04	0.04
M12	**Item Number:**	302190	2159555	39325	2065984	317930
	Efficiency Value:	0.36	0.36	0.37	0.38	0.38
M12st	**Item Number:**	302190	2159555	39325	317930	249109
	Efficiency Value:	0.36	0.36	0.37	0.37	0.38
M14	**Item Number:**	302190	2065984	2159555	39325	302298
	Efficiency Value:	0.19	0.19	0.19	0.22	0.24

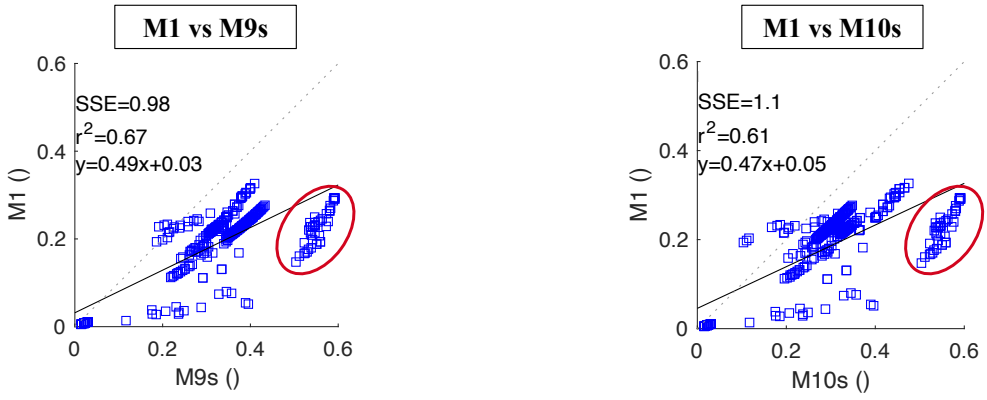


Figure 5.2: Regression analysis for M9s-M1 and M10s-M1 - data points identified as inconsitent are highlighted and will be further analysed.

In certain instances, this approach proved arduous and time-consuming and, to address these cases, a falsification methodology was employed, wherein examples of value curves for each criterion were examined to determine whether the method satisfied the given criteria.

For the cases where it is possible to easily isolate the non-compliant scenarios from the compliant ones, the model was set as compliant with the condition since it is possible to formulate a case distinction logic with a low implementation effort. This scenario is particularly true for cases where negative values are involved, especially in the intermediate calculations.

The results of this evaluation are shown in Table 5.7.

Table 5.7: Minimum criteria fulfillment assessment by method with only M9s fulfilling all the conditions without restrictions.

Method	Mirror Condition	Time Increment Condition	Value Decrement
M1	Yes	No	No
M2	Yes	No	No
M3	No	Yes	Yes
M3s	No	Yes	Yes
M4s	No	Yes	No
M4As	No	Yes	No
M5s	No	Yes	Yes
M6s	Yes	Yes	No
M7s	No	Yes	No
M7As	No	Yes	No
M8s	Yes	Yes	No
M9s	Yes	Yes	Yes[1]
M10s	Yes	Yes	Yes
M11	Yes	Yes	Yes[1]
M11st	Yes	Yes	Yes[1]
M11w	Yes	Yes	Yes[1]
M11wst	Yes	Yes	Yes[1]
M12	Yes	?	Yes[1]
M12w	Yes	?	Yes[1]
M12st	Yes	?	Yes[1]
M12wst	Yes	?	Yes[1]
M13	Yes	No	No
M13st	Yes	No	No
M14	Yes	Yes	No

5.4 Causes of inconsistency

There was a pattern in the dispersion of points that suggested an asymmetry against Nienhaus, depending on the value curve configuration. Figure 5.3 shows two scaled value curves, for item numbers A and B, that represent the pattern where the differences against Nienhaus are bigger.

After analysing the value curves that were generating this kind of behaviour, M9s and M10s under-performed in scenarios with a low number of steps (for example, two steps value curves) and, simultaneously, with a first short and low value added step compared with the remaining ones - which is the case in item number A and that repeats over several items across the portfolio. For this line item, using Nienhaus' calculation method, the overall efficiency is 5%, while using

[1]Depending on the case, the condition is partially fulfilled - need for case distinction.

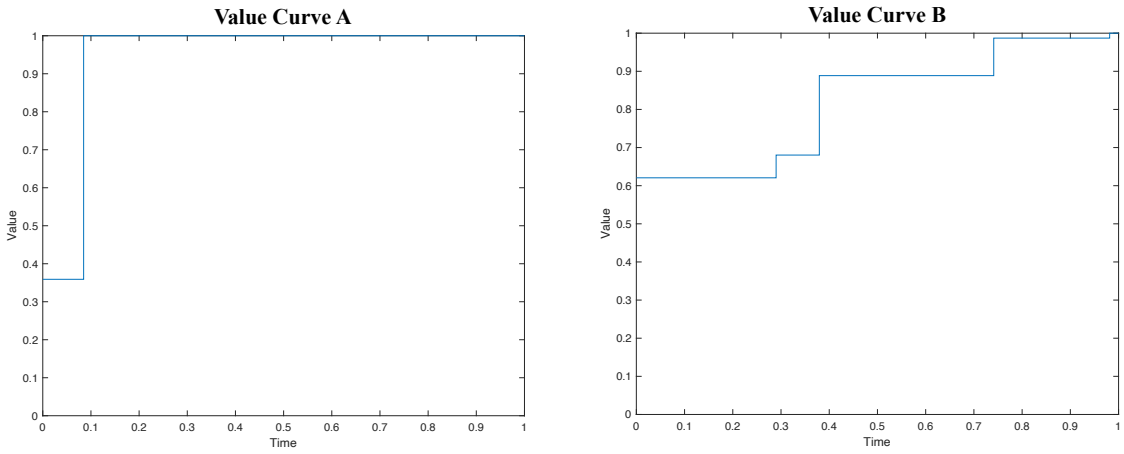


Figure 5.3: Value curves for items A and B showing the typical pattern of inconsistent points.

M9s and M10s the values significantly higher - 39%. It is possible to interpret that the Nienhaus' calculation adheres much better to the reality than the alternative methods proposed.

Furthermore, in cases where the first steps represents a significant share of the overall value and time, the models performance is also affected - for example, for item number B the first step represents more than 60% of the total added value and almost 30% of the time. For this case, the diffence between the methods is smaller: with M1 the efficiency is 18%, while M9s yields a 30% result and 37% is the result obtained by applying M10s.

5.5 Summary of overall results

The portfolios of products analysed consist of innovative products within the construction industry, aligned with Hilti's positioning. Generally, the items showed a low flow efficiency, in line with what was expected from a theoretical perspective. This suggested that flow efficiency calculation based on value curves could provide relevant information regarding how these products are positioned in terms of costs and responsiveness and regarding their performance compared with the supply chain strategy defined for them.

Looking at the results of the methods under analysis, M9s and M10s were the ones that showed the most consistent results. These methods had basic statistical properties that are aligned with what was expected for the dataset under evaluation. Then, they ranked the observations in a similar way to M1, with the divergences being clearly identified - two-step observations where the models under-performed or observations where the first step represented a large share of the overall process. However, M1, M9s and M10s ranked the least efficiency products in the same way, which confirms their good performance, taking into account that M1 performs particularly well in these circumstances.

To overcome the challenges identified, it was proposed to set a cut-off defining which method to apply, according to the characteristics of the value curve. Therefore, a novel calculation was

created to address the root causes of inconsistency across the spectrum of possible value curve configurations. For two-step value curves and value curves where the first step represents more than 50% of the total value and more than 25% of the total time, M2 should be applied, instead of the proposed M9s and M10s methods.

It was observed that both M9s and M10s performed well compared with the remaining models in every step of the evaluation. However, they consistently yielded similar results: firstly, the same average and standard deviation; secondly, the Bland & Altman analysis between them showed a coefficient of 0.96 in regression, a R^2 of 0.91 and a RPC of 0.09; thirdly, the Bland & Altman analysis against Nienhaus also has similar results; lastly, the same happened for the Spearman's coefficient and for the extreme cases. Consequently, distinguishing between the two methods based on their performance alone became impossible. Comparatively speaking, the M9s model has a slight advantage over the M10s model because of the simplicity of its formulation, however M10s fulfills the value decrement minimum criteria, while M9s does not for all the cases.

However, looking at the overarching research project, the results were considered very encouraging since M9s and M10s represent two fundamentally different concepts for flow efficiency calculation.

Chapter 6

Conclusion

6.1 Scientific Contributions

This work aimed to evaluate flow efficiency calculation methods. Their applicability, accuracy and reliability in assessing flow efficiency across the supply chain were examined by applying the evaluation framework proposed by Sieben (2023).

Firstly, this study offers a comprehensive understanding of the existing flow efficiency calculation methods and their performance by using 390 data cases to evaluate them. This statistically sufficient number allowed the identification and correction of flaws in the methods.

In addition, this work contributed to showing that two hitherto unevaluated flow efficiency calculation methods yield statistically acceptable results.

Finally, the cases where the results of these two methods were apparently not entirely correct were identified and codified and a workaround was proposed.

These assessments can be helpful in the definition of best practices in the supply chain of different products, at the moment that they can be the basis of improvements and recommendations based on the examination of value curves as per offered by this study.

6.2 Practical Contributions

Although the final proposed flow efficiency calculation method was not implemented in practice, it has laid the basis for improvement measures at Hilti, in a project stream which is not part of this thesis. Given the robustness of the calculation, the project stakeholders are confident that this method, together with a model to predict the efficiency of products based on their characteristics, could hopefully identify under performing items which could then be the target of a closer analysis.

6.3 Limitations of this research

The following limitations should be acknowledged. Firstly, the detection of outliers was purely inductive and no further investigation was done regarding the heterogeneity of the dataset, meaning

that the data does not fully represent all possible scenarios and variations in supply chains, a claim that has a black swan aspect to it (Taleb, 2008). The study was conducted in one single company and with a limited number of observations which also contributes for the transferability limitations.

It is also important to point out that within the observations there was no value decrement observations, making the test of this criteria across the models impossible. And since there are no data points where the M1 calculated flow efficiency is significantly higher than by using M9s and M10s, the time increment condition testing might also have been limited in the practical context. Still on the minimum criteria evaluation, the application of the falsification methodology, despite the significant confidence about the classification of a method as non-compliant with a certain condition, it does not rule out the possibility of overlooking specific scenarios for the compliant models.

In addition, using production steps as a proxy for the entire supply chain may oversimplify the complexity and variability of real-world supply chains. An oversimplification was also identified in the usage of cost values as a proxy for the value of each step of the value curve.

Lastly, except for the three minimum criteria no further deductive, let alone deterministic, evaluation of the completeness was performed. Also, since there is no formal and validated method, the comparison against an unknown benchmark proved to be challenging.

6.4 Suggestions for future research

There are several potential avenues for further research in the field of supply chain efficiency measurement.

One could focus on applying and validating the newly proposed model in a practical context. Eventually, with the collaboration of practitioners, researchers, and organizations, it would be possible to develop a validated and widely accepted method that can accurately assess flow efficiency across different supply chains and industries and that could be used as a standard and benchmark.

In addition, further research could focus on identifying products with fundamentally different value curves, i.e., divergent production setups and apply the method to these areas, for example, the chemical industry or even services.

Finally, future research could explore the integration of emerging technologies, such as artificial intelligence and machine learning, in supply chain efficiency measurement. These technologies have the potential to analyze large volumes of data. For example, by applying image recognition to the plotted value curves, it could be possible to calculate the efficiency and provide real-time insights for continuous improvement in supply chain management, by exclusively looking at the shape of the curves.

Bibliography

Akoglu, H. (2018). User's guide to correlation coefficients. *Turkish Journal of Emergency Medicine*, pages 91–93.

Bauer, P. W., Berger, A. N., Ferrier, G. D., and Humphrey, D. B. (1998). Consistency conditions for regulatory analysis of financial institutions: A comparison of frontier efficiency methods. *Journal of Economics and Business*, 50(2):85–114.

Bley, N. (2022). Supply Chain Efficiency: Entwicklung einer Methodik zur quantitativen Bewertung von Lieferketten am Beispiel der Hilti AG.

Blinder, A. and Maccini, L. (1991). The resurgence of inventory research: what have we learned? *Journal of Economic Surveys*, 5:291–328.

Brennan, M., Maksimovic, V., and Zechner, J. (1988). Vendor financing. *Journal of Finance*, pages 1127–1141.

Burger, A. (2008). *Produktivität und Effizienz in Banken*.

Chopra, S. and Meindl, P. (2006). Supply chain performance: Achieving strategic fit and scope. *Supply Chain Management: Strategy, Planning, and Operations*, (2006):22–42.

Cooper, W. W., Seiford, L. M., and Zhu, J. (2003). Data Envelopment Analysis - History, Models and Interpretations. pages 1 – 39.

CSCMP (2013). *Supply Chain Management Terms and Glossary*. Council of Supply Chain Management Professionals.

Danert, G. (1988). *Wirtschaftliche Gestaltung der Fertigungslogistik : Herrn Prof. Dr. Günter Danert zum 75. Geburtstag*. Stuttgart. Literaturangaben am Ende der einzelnen Kapitel Literaturangaben am Ende der einzelnen Kapitel.

Daraio, C. and Simar, L. (2007). *Advanced Robust and Nonparametric Methods in Efficiency Analysis, Methodology and Applications*. Studies in Productivity and Efficiency.

Deloof, M. (2003). Does working capital management affect profitability of belgian firms? *Journal of Business Finance & Accounting*, pages 573–587.

Dyckhoff, H. (2003). *Grundzüge der Produktionswirtschaft, Einführung in die Theorie betrieblicher Wertschöpfung*.

Eljelly, A. M. A. (2004). Liquidity-profitability trade-off: An empirical investigation in an emerging market. *International Journal of Commerce and Management*, 14(2):48–61.

Emery, G. (1984). A pure financial explanation for trade credit. *Journal of Financial and Quantitative Analysis*, pages 271–285.

Fisher, M. L. (1997). What is the right supply chain for your product? *Harvard Business Review*, pages 105–116.

Forrester, J. W. (1958). Industrial dynamics: A major breakthrough for decision makers. *Harvard Business Review*, 36:37–66.

Giavarina, D. (2015). Understanding bland altman analysis. *Biochemia Medica*, 25(2):141–151.

Gomes, S. (2021). A Performance Pricing methodology based on capital efficiency to improve supply chain performance.

Harris, G. A. (2007). *Alignment of Supply Chain Strategy with Product Characteristics*. PhD thesis, University of Alabama in Huntsville.

Heizer, J. (2008). *Principles of Operations Management*. Pearson, 7th edition.

Herbrüggen, H. S. (1991). *Modellanalyse von Materialflußsystemen für eine kundennahe Produktion eine empirische Untersuchung*. PhD thesis. ISBN: 3890122345 Dis. an der Uni Passau.

Hilti (2023). Financial report 2022.

Huang, S. H., Uppal, M., and Shi, J. (2002). A product-driven approach to manufacturing supply chain selection. *Supply Chain Management: An International Journal*, 7(4):189–199.

Katharakis, G., Katharaki, M., and Katostaras, T. (2014). An empirical study of comparing DEA and SFA methods to measure hospital units' efficiency. *International Journal of Operational Research*, 21(3):341.

Kaynak, H. (2003). The relationship between total quality management practices and their effects on firm performance. *Journal of Operations Management*, 21:405–435.

Kieschnick, R., Laplante, M., and Moussawi, R. (2013). Working Capital Management and Shareholders' Wealth*. *Review of Finance*, pages 1827–1852.

Klein, C. (2021). Supply Chain Efficiency: A Methodical Comparison between a Value Curve-based Approach and Data Envelopment Analysis.

Klein, R. (2023). Bland-Altman and Correlation Plot. MATLAB Central File Exchange, Available at: https://www.mathworks.com/matlabcentral/fileexchange/45049-bland-altman-and-correlation-plot.

Kopczak, L. R. and Johnson, M. E. (2003). The supply-chain management effect. *MIT Sloan Management Review*.

Lee, H. L. and Billington, C. (1992). Managing supply chain inventory: pitfalls and opportunities. *MIT Sloan Management Review*.

Leontitsis, A. (2023). Spearman Rank Correlation. MATLAB Central File Exchange, Available at: https://www.mathworks.com/matlabcentral/fileexchange/4374-spearman-rank-correlation.

Li, S., Ragu-Nathan, B., Ragu-Nathan, T., and Subba Rao, S. (2006). The impact of supply chain management practices on competitive advantage and organizational performance. *Omega*, 34(2):107–124.

Mansournia, m. a., Waters, R., Nazemipour, M., Bland, M., and Altman, D. (2020). Bland-altman methods for comparing methods of measurement and response to criticisms. *Global Epidemiology*.

Mason-Jones, R., Naylor, B., and Towill, D. R. (2000). Lean, agile or leagile? matching your supply chain to the marketplace. *International Journal of Production Research*, 38(17):4061–4070.

Musacchia, G. (2019). Assessment of Optimal Inventory Levels in Supply Chain: Development of an Innovative Model and Implementation in a Real Case.

Nienhaus, J. (2004). Modelling, analysis, and improvement of supply chains - a structured approach.

Näf, P. (2015). Supply chain efficiency at hilti – logistical efficiency valuation methods in a theoretical context and application of a new approach at hilti.

Parlak, E. and Pescalli, Z. (2023). Improving the Calculation of the Flow Efficiency through Machine Learning.

Petersen, M. and Rajan, R. (1997). Trade credit: Theories and evidence. *Review of Financial Studies*, pages 661–691.

Porter, M. E. (2001). The value chain and competitive advantage. *Understanding business processes*, pages 50–66.

Prockl, G. (2001). *Supply Chain Management als Gestaltung überbetrieblicher Versorgungsnetzwerke*. PhD thesis.

Putkivaara, L. (2020). Inventory Optimisation By Means of Multivariate Analysis.

Reddy, D. R. and Kameswari, P. (2004). Working capital management practices in pharma industry: A case study of 'cipla limited'. *Management Accountant*, page 638–44.

Scheel, H. (2000). *Effizienzmaße der Data Envelopment Analysis*. PhD thesis.

Schiff, M. and Lieber, Z. (1974). A model for the integration of credit and inventory management. *Journal of Finance*, page 133–140.

Schober, P., Boer, C., and Schwarte, L. A. (2018). Correlation coefficients: appropriate use and interpretation. *Anesthesia & analgesia*, 126(5):1763–1768.

Schulte, C. (1999). *Logistik Wege zur Optimierung des Material- und Informationsflusses*. Vahlen, München, 3., überarb. und erw. aufl. edition.

Sieben, B. (2023). PhD thesis.

Sieben, B., Parlak, E., Rodrigues, T., Näf, P., Bley, N., Klein, C., Wolf, B., Witthaut, M., Costa, F., Carvalho, H., Trucco, P., and Bode, C. (2023). Making supply chains more efficient: A novel and robust value curve-based evaluation methods. *under submission*.

Slomka, M. (1989). *Methoden der Schwachstellen- und Ursachenanalyse in logistischen Systemen eine empirische Untersuchung*. PhD thesis.

Stern, C. and Stalk Jr., G. (1998). *Perspectives on Strategy from the BCG*. Boston Consulting Group, Boston, MA.

Taleb, N. N. (2008). *The Black Swan: The Impact of the Highly Improbable*. Random House, 1 edition.

Thampi, P. (2018). Logistical Efficiency Drivers in a Theoretical Approach and Application within the Hilti Context.

Ulrich, H. (1981). Die betriebswirtschaftslehre als anwendungsorientierte sozialwissenschaft. *Die Führung des Betriebes, Stuttgart*, 1981:1–25.

VDI - Verein Deutscher Ingenieure (2018). Performance pricing (PP) - fundamentals and application. Technical Standard 2817 1.

Wilner, B. (2000). The exploitation of relationship in financial distress: The case of trade credit. *Journal of Finance*, 55(2):153–178.

Wirth, R. and Hipp, J. (2000). CRISP-DM: Towards a standard process model for data mining. In *Proceedings of the 4th international conference on the practical applications of knowledge discovery and data mining*, volume 1, pages 29–39. Manchester.

Wolf, B. (2020). Wertkurven in der Hilti AG - Anwendungen von Wertkurven im Supply Chain Controlling.

Zachau, T. (1995). *Prozeßgestaltung in industriellen Anlagengeschäften*. PhD thesis. Zugl. Diss., Univ. München, 1994.

Özgür Doğan, N. (2018). Bland-altman analysis: A paradigm to understand correlation and agreement. *Turkish Journal of Emergency Medicine*, pages 139–141.

Appendix A

Bland & Altman and Spearman coefficients

Table A.1: Regression coefficient for a simple regression without intercept between methods.

	M1	**M2**	**M3**	**M3s**	**M4s**	**M4As**	**M5s**	**M6s**	**M7s**	**M7As**	**M8s**	**M9s**	**M10s**	**M11**	**M11st**	**M11w**	**M11wst**	**M12**	**M12w**	**M12st**	**M12wst**	**M13**	**M13st**	**M14**
M1	1.00																							
M2	0.74	1.00																						
M3	-19.61	-24.22	1.00																					
M3s	0.81	0.87	-0.01	1.00																				
M4s	-1.53	-1.32	0.04	-0.60	1.00																			
M4As	-0.68	-0.57	0.02	0.02	0.40	1.00																		
M5s	1.20	0.88	-0.02	0.38	-1.02	-1.64	1.00																	
M6s	1.20	0.88	-0.02	0.38	-1.02	-1.64	1.00	1.00																
M7s	-2.65e+11	-9.28e+10	4.29e+9	-2.36e+11	1.54e+11	4.51e+11	-2.35e+11	-2.35e+11	1.00															
M7As	0.13	0.18	-0.01	0.05	-0.03	-0.01	0.00	0.00	-0.00	1.00														
M8s	-0.19	0.13	-0.01	-0.01	0.15	0.30	-0.18	-0.18	0.00	1.52	1.00													
M9s	0.49	0.32	-0.01	0.19	-0.23	-0.27	0.16	0.16	0.00	0.82	-0.53	1.00												
M10s	0.47	0.29	-0.01	0.19	-0.21	-0.28	0.14	0.14	0.00	0.52	-0.56	0.96	1.00											
M11	0.35	0.22	-0.00	0.47	-0.17	0.07	0.05	0.05	0.00	0.91	-0.29	1.10	1.26	1.00										
M11st	0.43	0.35	-0.01	0.14	-0.11	-0.15	0.03	0.03	-0.00	1.35	-0.06	0.61	0.73	0.33	1.00									
M11w	-0.23	-0.58	0.03	0.05	-0.07	-0.06	0.15	0.15	0.00	-3.69	-1.23	0.39	0.50	0.30	-0.44	1.00								
M11wst	0.25	-0.36	0.01	0.25	-0.19	-0.11	0.14	0.14	0.00	-1.78	-1.37	1.32	1.46	0.77	0.87	0.77	1.00							
M12	1.03	0.98	-0.04	-0.18	-0.51	-1.32	0.48	0.48	-0.00	2.16	-0.71	1.01	0.86	-0.62	0.65	-0.53	-0.28	1.00						
M12w	2.26	-0.29	0.04	0.88	-1.39	-1.82	1.24	1.24	0.00	-8.33	-7.46	6.85	6.88	2.42	0.88	3.76	2.67	0.23	1.00					
M12st	0.89	1.03	-0.04	-0.14	-0.30	-0.89	0.22	0.22	-0.00	3.32	0.11	0.63	0.52	-0.44	0.79	-0.80	-0.33	0.71	-0.04	1.00				
M12wst	3.58	2.75	-0.08	0.38	-1.17	-2.31	0.74	0.74	-0.00	5.56	-2.65	5.15	5.24	0.92	4.05	-0.39	0.88	1.31	0.35	1.79	1.00			
M13	1.09	1.36	-0.05	0.24	-0.37	-0.63	0.21	0.21	0.00	5.59	0.55	0.97	0.88	0.10	1.32	-0.97	-0.31	0.55	-0.06	0.84	0.20	1.00		
M13st	0.30	0.44	-0.02	0.01	-0.06	-0.17	0.01	0.01	-0.00	1.78	0.36	0.11	0.13	-0.05	0.55	-0.42	-0.16	0.19	-0.05	0.32	0.07	0.33	1.00	
M14	0.86	0.69	-0.02	0.14	-0.33	-0.60	0.22	0.22	-0.00	1.42	-0.64	1.34	1.31	0.25	0.84	-0.05	0.24	0.33	0.10	0.44	0.23	0.32	0.65	1.00

Table A.2: R^2 for a simple regression with intercept between methods.

	M1	**M2**	**M3**	**M3s**	**M4s**	**M4As**	**M5s**	**M6s**	**M7s**	**M7As**	**M8s**	**M9s**	**M10s**	**M11**	**M11st**	**M11w**	**M11wst**	**M12**	**M12w**	**M12st**	**M12wst**	**M13**	**M13st**	**M14**
M1	1.00																							
M2	0.64	1.00																						
M3	0.51	0.65	1.00																					
M3s	0.18	0.17	0.04	1.00																				
M4s	0.52	0.33	0.21	0.29	1.00																			
M4As	0.36	0.22	0.22	0.00	0.56	1.00																		
M5s	0.26	0.12	0.06	0.10	0.84	0.63	1.00																	
M6s	0.26	0.12	0.06	0.10	0.84	0.63	1.00	1.00																
M7s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00															
M7As	0.33	0.56	0.66	0.20	0.09	0.00	0.00	0.00	0.00	1.00														
M8s	0.09	0.04	0.07	0.00	0.26	0.27	0.41	0.41	0.00	0.27	1.00													
M9s	0.67	0.24	0.14	0.39	0.69	0.26	0.39	0.39	0.00	0.09	0.33	1.00												
M10s	0.61	0.19	0.11	0.37	0.57	0.28	0.32	0.32	0.00	0.04	0.37	0.91	1.00											
M11	0.11	0.04	0.00	0.73	0.11	0.01	0.01	0.01	0.00	0.04	0.03	0.38	0.50	1.00										
M11st	0.41	0.24	0.30	0.17	0.12	0.06	0.01	0.01	0.01	0.20	0.00	0.29	0.42	0.26	1.00									
M11w	0.05	0.25	0.52	0.01	0.02	0.00	0.10	0.10	0.00	0.59	0.56	0.05	0.08	0.09	0.08	1.00								
M11wst	0.03	0.06	0.09	0.12	0.08	0.01	0.06	0.06	0.01	0.08	0.41	0.32	0.40	0.34	0.18	0.35	1.00							
M12	0.33	0.25	0.46	0.04	0.37	0.69	0.40	0.40	0.00	0.07	0.06	0.11	0.08	0.13	0.06	0.10	0.05	1.00						
M12w	0.17	0.00	0.04	0.10	0.29	0.15	0.29	0.29	0.00	0.12	0.78	0.56	0.57	0.22	0.01	0.54	0.46	0.01	1.00					
M12st	0.40	0.44	0.71	0.03	0.20	0.51	0.14	0.14	0.00	0.27	0.00	0.07	0.05	0.11	0.14	0.36	0.11	0.83	0.02	1.00				
M12wst	0.80	0.40	0.33	0.03	0.38	0.43	0.19	0.19	0.00	0.09	0.18	0.59	0.61	0.06	0.46	0.01	0.09	0.35	0.23	0.40	1.00			
M13	0.52	0.69	0.91	0.10	0.27	0.22	0.11	0.11	0.00	0.67	0.06	0.15	0.12	0.01	0.34	0.47	0.08	0.43	0.05	0.62	0.28	1.00		
M13st	0.26	0.47	0.72	0.00	0.05	0.11	0.00	0.00	0.00	0.46	0.16	0.01	0.02	0.01	0.40	0.59	0.14	0.36	0.19	0.62	0.22	0.73	1.00	
M14	0.76	0.42	0.32	0.07	0.52	0.49	0.29	0.29	0.01	0.10	0.18	0.66	0.63	0.07	0.33	0.00	0.11	0.37	0.28	0.39	0.88	0.25	0.15	1.00

Table A.3: RPC for a simple regression without intercept between methods.

	M1	**M2**	**M3**	**M3s**	**M4s**	**M4As**	**M5s**	**M6s**	**M7s**	**M7As**	**M8s**	**M9s**	**M10s**	**M11**	**M11st**	**M11w**	**M11wst**	**M12**	**M12w**	**M12st**	**M12wst**	**M13**	**M13st**	**M14**
M1	0.00																							
M2	0.12	0.00																						
M3	0.18	0.20	0.00																					
M3s	0.16	0.17	0.09	0.00																				
M4s	0.24	0.25	0.08	0.15	0.00																			
M4As	0.29	0.30	0.15	0.18	0.11	0.00																		
M5s	0.15	0.18	0.08	0.10	0.15	0.22	0.00																	
M6s	0.15	0.18	0.08	0.10	0.15	0.22	0.00	0.00																
M7s	0.18	0.19	0.01	0.09	0.08	0.15	0.07	0.07	0.00															
M7As	0.71	0.66	0.80	0.76	0.82	0.82	0.79	0.00	0.79	0.00														
M8s	0.36	0.30	0.27	0.29	0.24	0.23	0.32	0.32	0.00	0.69	0.00													
M9s	0.18	0.26	0.30	0.25	0.37	0.40	0.26	0.26	0.30	0.76	0.50	0.00												
M10s	0.19	0.27	0.30	0.25	0.36	0.40	0.26	0.26	0.29	0.79	0.51	0.09	0.00											
M11	0.20	0.23	0.17	0.10	0.21	0.22	0.17	0.17	0.17	0.78	0.34	0.23	0.21	0.00										
M11st	0.20	0.24	0.27	0.24	0.30	0.34	0.27	0.27	0.26	0.71	0.39	0.27	0.23	0.23	0.00									
M11w	0.27	0.31	0.16	0.18	0.19	0.23	0.16	0.16	0.17	0.93	0.41	0.31	0.29	0.20	0.35	0.00								
M11wst	0.20	0.25	0.13	0.13	0.17	0.21	0.13	0.13	0.13	0.84	0.37	0.25	0.23	0.14	0.24	0.14	0.00							
M12	0.14	0.17	0.10	0.15	0.16	0.24	0.08	0.08	0.10	0.77	0.31	0.28	0.28	0.22	0.26	0.22	0.18	0.00						
M12w	0.16	0.19	0.03	0.09	0.10	0.17	0.06	0.06	0.03	0.80	0.30	0.27	0.27	0.15	0.26	0.14	0.11	0.10	0.00					
M12st	0.14	0.14	0.13	0.17	0.18	0.26	0.12	0.12	0.12	0.74	0.29	0.29	0.29	0.24	0.24	0.26	0.20	0.05	0.13	0.00				
M12wst	0.14	0.17	0.05	0.09	0.12	0.19	0.07	0.07	0.04	0.78	0.29	0.26	0.26	0.16	0.23	0.18	0.12	0.08	0.04	0.10	0.00			
M13	0.12	0.11	0.12	0.12	0.17	0.23	0.12	0.12	0.12	0.70	0.27	0.27	0.27	0.20	0.22	0.26	0.19	0.09	0.13	0.08	0.10	0.00		
M13st	0.26	0.22	0.31	0.31	0.33	0.38	0.31	0.31	0.30	0.63	0.32	0.40	0.39	0.36	0.24	0.44	0.37	0.25	0.32	0.22	0.28	0.21	0.00	
M14	0.09	0.16	0.18	0.18	0.24	0.31	0.15	0.15	0.18	0.75	0.38	0.18	0.19	0.21	0.22	0.25	0.18	0.14	0.16	0.14	0.14	0.16	0.28	0.00

Table A.4: Spearman's coefficient between methods.

	M1	M2	M3	M3s	M4s	M4As	M5s	M6s	M7s	M7As	M8s	M9s	M10s	M11	M11st	M11w	M11wst	M12	M12w	M12st	M12wst	M13	M13st	M14
M1	1.00																							
M2	0.79	1.00																						
M3	-0.65	-0.75	1.00																					
M3s	0.57	0.58	-0.33	1.00																				
M4s	-0.64	-0.53	0.35	-0.71	1.00																			
M4As	-0.41	-0.33	0.43	-0.23	0.61	1.00																		
M5s	0.57	0.40	-0.28	0.60	-0.97	-0.65	1.00																	
M6s	0.57	0.40	-0.28	0.60	-0.97	-0.65	1.00	1.00																
M7s	0.16	0.14	0.10	0.15	0.05	0.11	0.13	0.13	1.00															
M7As	0.57	0.73	-0.70	0.55	-0.42	-0.01	0.30	0.30	0.13	1.00														
M8s	-0.45	-0.19	-0.01	-0.31	0.64	0.52	-0.75	-0.75	0.14	0.11	1.00													
M9s	0.73	0.45	-0.29	0.73	-0.90	-0.46	0.87	0.87	0.17	0.42	-0.58	1.00												
M10s	0.73	0.45	-0.45	0.65	-0.71	-0.67	0.69	0.69	0.16	0.23	-0.53	0.81	1.00											
M11	0.61	0.40	-0.38	0.74	-0.65	-0.59	0.62	0.62	0.12	0.30	-0.44	0.74	0.90	1.00										
M11st	0.57	0.38	-0.56	0.41	-0.32	-0.54	0.28	0.28	0.14	0.25	-0.17	0.47	0.78	0.79	1.00									
M11w	0.72	0.47	-0.20	0.72	-0.82	-0.39	0.77	0.77	0.19	0.34	-0.54	0.91	0.72	0.71	0.39	1.00								
M11wst	0.51	0.25	-0.19	0.40	-0.28	-0.43	0.20	0.20	0.15	-0.00	-0.22	0.46	0.72	0.75	0.81	0.52	1.00							
M12	0.48	0.47	-0.74	0.06	-0.40	-0.62	0.40	0.40	0.11	0.48	-0.10	0.29	0.33	0.24	0.39	0.15	0.07	1.00						
M12w	0.65	0.39	-0.12	0.55	-0.79	-0.39	0.73	0.73	0.19	0.26	-0.56	0.84	0.64	0.57	0.26	0.89	0.47	0.16	1.00					
M12st	0.42	0.52	-0.80	-0.04	-0.22	-0.56	0.19	0.19	0.12	0.49	0.10	0.12	0.24	0.15	0.41	0.01	0.07	0.93	0.02	1.00				
M12wst	0.72	0.44	-0.44	0.23	-0.35	-0.54	0.29	0.29	0.18	0.06	-0.34	0.48	0.74	0.57	0.70	0.49	0.77	0.31	0.50	0.35	1.00			
M13	0.76	0.85	-0.95	0.45	-0.54	-0.44	0.45	0.45	0.14	0.77	-0.15	0.46	0.50	0.39	0.49	0.36	0.15	0.73	0.28	0.75	0.45	1.00		
M13st	0.33	0.52	-0.79	0.02	0.01	-0.21	-0.10	-0.10	0.15	0.48	0.38	-0.05	0.15	0.01	0.33	-0.16	-0.02	0.57	-0.22	0.74	0.34	0.72	1.00	
M14	0.51	0.24	-0.22	0.21	-0.44	-0.52	0.40	0.40	0.19	-0.06	-0.27	0.53	0.63	0.49	0.48	0.55	0.64	0.20	0.64	0.19	0.76	0.24	0.11	1.00