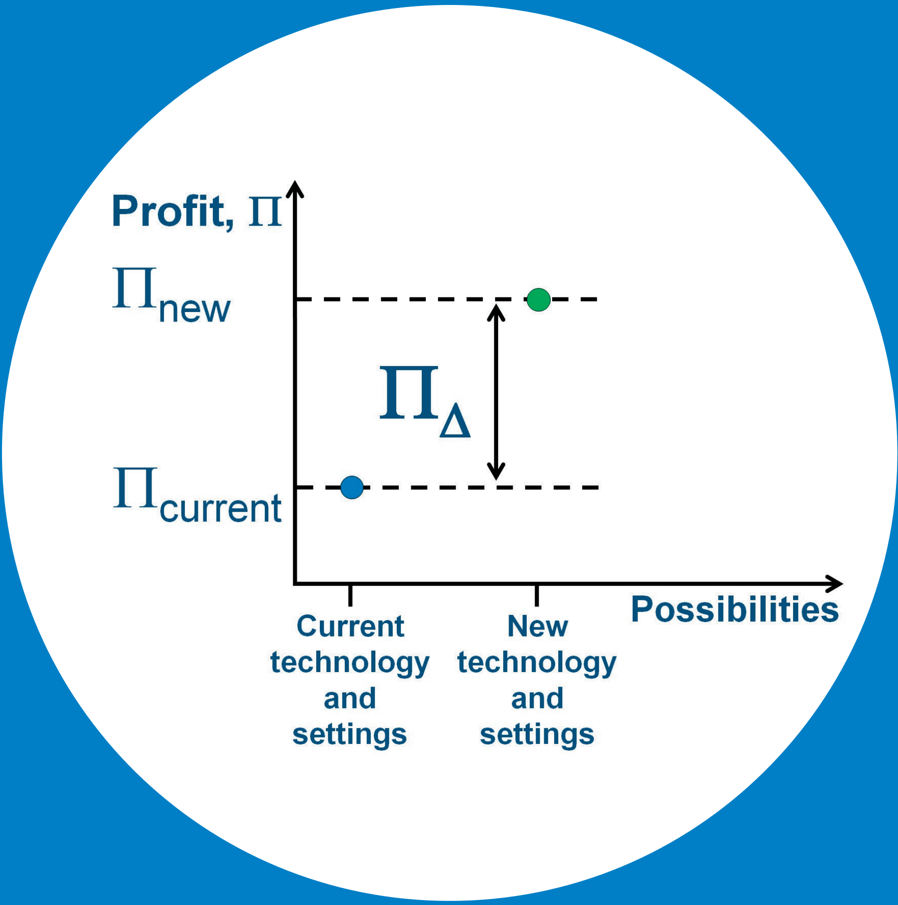
Department of Engineering Design and Production

A novel profit potential calculation method applied to web manufacturing

Riku Pihko



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A novel profit potential calculation method applied to web manufacturing

Riku Pihko

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Abstract

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Abstract

The classical competitive firm is continuously searching for new ways to maximise profit. For this purpose there exist several methods to identify sources of losses and to calculate profitability or productivity of a production unit. However, the existing methods do not provide adequate information of how to calculate the profit potential related to changes in technology and process parameters. This research question is crucial in order to be able to target the development and investment efforts effectively. Therefore, there is a need to carry out this research work. As a conclusion of the research, a novel profit potential calculation method is developed in this dissertation.

This study applies a constructive research approach to develop a novel profit potential calculation method suitable for web manufacturing processes. The theoretical framework is the profit function, which is further developed to form the web profit model. The profit model is optimised with respect to technology and process related input parameters to form the profit potentials. Then, new concepts: profit potentials at different optimisation levels of increasing complexity are presented. Sensitivity and uncertainty calculations are included in the method and the method is applied to two web process case examples. Method application is presented as a continuous process and the principles of the method application to other products or processes are presented.

The findings show that the created profit potential method can be applied to web process profit potential analysis. Based on the profit potentials found it can be claimed that this novel method combined with new technology assessment, brings out significant potential to improve the profitability of the web processes. The accuracy and scope of the calculation can be further improved by model development. To ensure continuous profit growth, the novel method application can be implemented as a continuous process. In addition, this novel method can be applied to different types of products and processes and also optimal resource planning by introducing new parameters and models.

Keywords web, paper, board, tissue, machine, process, production, technology, method, calculation, improvement, profit, potential, optimisation

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Tiivistelmä

Tekijä
Riku Pihko

Väitöskirjan nimi
Uusi tuottopotentiaalin laskentamenetelmä sovellettuna radan valmistukseen

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Tiivistelmä

Klassinen kilpailukykyinen yritys etsii jatkuvasti uusia tapoja tuoton maksimoimiseksi. Tähän tarkoitukseen on useita menetelmiä, joilla voidaan tunnistaa tappioiden lähteitä sekä joilla voidaan laskea tuotantoyksikön kannattavuutta ja tuottavuutta. Olemassa olevat menetelmät eivät kuitenkaan tarjoa riittävää tietoa siitä kuinka voidaan laskea teknologian ja prosessiparametrien muutoksiin liittyvä tuottopotentiaali. Tämä tutkimuskysymys on ratkaiseva, jotta kehitys- ja investointipanostukset voidaan kohdistaa tehokkaasti. Tämän tutkimuskysymyksen selvittämiseen tarvitaan tutkimustyötä. Tutkimustyön seurauksena tässä työssä kehitetään uusi tuottopotentiaalin laskentamenetelmä.

Tämä tutkimus soveltaa konstruktiivista tutkimustapaa uuden radanvalmistusprosesseille soveltuvan tuottopotentiaalin laskentamenetelmän kehittämiseen. Teoreettinen viitekehys on tuottofunktio, jota kehitetään edelleen ja muodostetaan radantuottomalli. Radantuottomalli optimoidaan teknologiaan ja prosessiin liittyvien parametrien suhteen ja muodostetaan tuottopotentiaalit. Uudet käsitteet, tuottopotentiaalit eri kasvavan kompleksisuuden optimointitasoilla, esitetään. Herkkyyden ja epävarmuuden laskenta lisätään menetelmään ja menetelmän soveltaminen esitetään kahden esimerkkitapauksen avulla. Tämän jälkeen kuvataan kuinka menetelmää voidaan soveltaa jatkuvana prosessina ja lisäksi esitetään periaatteet menetelmän soveltamiseksi erilaisille tuotteille ja prosesseille.

Tulokset osoittavat, että aikaansaatua tuottopotentiaalin laskentakehystä voidaan soveltaa radanvalmistuksen tuottopotentiaalianalyyseihin. Määritettyjen tuottopotentiaalien perusteella voidaan väittää, että uusi menetelmä sovellettuna uuden teknologian arviointiin tuo esiin merkittävää potentiaalia radanvalmistusprosessien kannattavuuden parantamiseksi. Menetelmän tarkkuutta ja laajuutta voidaan edelleen parantaa malleja kehittämällä. Jatkuvan tuottojen kasvattamisen varmistamiseksi menetelmää voidaan käyttää jatkuvana prosessina. Lisäksi uutta menetelmää voidaan soveltaa erityyppisille tuotteille ja prosesseille sekä optimaalisen resurssien käytön määrittämiseen soveltamalla uusia parametreja ja malleja.

Avainsanat rata, raina, paperi, kartonki, pehmopaperi, kone, prosessi, tuotanto, teknologia, menetelmä, laskenta, parannus, tuotto, potentiaali, optimointi

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PREFACE

This study was carried out at Metso Paper (Valmet) Jyväskylä and Aalto University (Helsinki University of Technology) Espoo during the years 2000-2015. Finalisation of this work was done at VTT. I would like to thank Metso Paper for financial support during this work. I would also like to thank Stora Enso, UPM-Kymmene, M-real, and Holmen Paper for providing production machine data and their personnel for support and advice during the research.

The motivation came from the need for a method, which can be applied to web manufacturing process profit potential assessment and optimisation. There exist several theories related to profit and production maximisation and product development of different types of products. However, these theories are either general or covering only one small part related to web manufacturing process profit optimisation. Therefore there was a clear need to develop a novel efficient method. The analysis of the existing theories and production machine data was a natural starting point, and is frequently discussed in this study. The pilot trials have also proved very fruitful in order to achieve new data needed for the models.

I would like to thank Professors Petri Kuosmanen and Seppo Virtanen for encouragement and guidance during the work. I would also like to thank the staff of Metso Paper Rautpohja, especially Jaakko Hakala and Jouko Yli-Kauppila for their support. I am also grateful to Tim Whale for English language checking and to Riku Suutari and Erkki Heikkola from Numerola for implementation of the method calculation tool. I also wish to thank the pre-examiners Professors Pekka Kess and Tuomo Kässi for their valuable comments on the thesis manuscript.

Finally, my dearest thanks go to my parents, brother and sister, in-laws, and especially to my wife Rebekka, and my daughter and son, Eleonoora and Onni. Their loving inspiration and support has made the completion of this work possible.

Jyväskylä, 28th of September, 2015

Riku Pihko

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NOMENCLATURE

Symbol	Definition
C	investment with fixed cost
l_v	lower bound vectors
LCP	Life Cycle Profit
PCC	Precipitated Calcium Carbonate
Π_c	current situation profit
$\Pi_{\Delta,1}$	profit potential achieved optimising driving parameters
$\Pi_{\Delta,2}$	profit potential achieved applying fixed investment and optimising driving parameters
$\Pi_{\Delta,3}$	profit potential achieved applying optimised investment and optimising driving parameters
$\pi_{mass,t}(x)$	profit per mass unit of product
$\Pi_t(x)$	profit for year t
q_i	process quantity
R	Residual value of the investment after the period of Y years
r_t	interest rate at year t
S	cost of web process line shutdown
SC	Super Calendered web
SQP	Sequential Quadratic Programming
u_v	upper bound vectors
x	input parameters
x_f	fixed input parameters, which remain unchanged
$x_{f,t}$	fixed input parameters, which can be changed annually
x_v	variable input parameters, which are constant over inspection period
$x_{v,t}$	variable input parameters that can be optimised separately each year
$y_t(x)$	web process saleable production
web	long, thin, and flexible material

1 INTRODUCTION

1.1 Profit maximisation, research question and profit potential definition

The classical competitive firm is continuously searching for new ways to maximise profit. The following definitions and explanations of profit are adopted (Diesen 1998):

- **Gross profit** or earnings before interest, taxes and depreciation (EBITD) indicates how much remains to cover necessary investments, payments to money lenders as interest and amortisation of debts, payments to the state as taxes, and to the shareholders as dividends. Gross margin is EBITD divided by sales.
- **Operating profit** or EBIT is defined as earnings before interest and taxes. Operating margin is operating profit (EBIT) divided by sales. This is a good measure of a company's financial performance.

To describe profit potential, the discussion presented by Quest (2002 and 2003) provides a good starting point. Quest advises that a different way of thinking is needed to unlock hidden potential: unrecorded and unnoticed losses.

Losses are important sources of potential. However, in addition to identified losses, there are also new possibilities to improve the current profit situation of a web production process. Possibilities consist of new technology, raw materials, products, and business ideas.

The effect of one single variable, for example a change in one production machine setting on the profit would be an interesting subject to study. However, it is even a more interesting research question to try to find out how to calculate the maximum profit achieved when many process and technology parameters are changed simultaneously and what would be the profit potential compared to the existing situation after the changes. To be able to carry out the research needed to solve this research question, first it is needed to define the profit potential. Then it should be defined which theories and methods are available to find out what type of research is needed to fill this gap between the existing knowledge and new knowledge.

In this study, profit potential is defined as follows: A profit potential is a gap between the profit produced applying the current technology and process settings, and the assessed profit achieved applying the new process technology and/or new process settings, calculated over a certain time period.

1.2 A need for a novel approach, research sub questions

Several studies have been carried out to establish different factors limiting profit of a production unit. Some of these studies are considering directly the profit, but most are applying indirect measures.

Coelli et al. (2001) apply a distance function based technique and presents the effect of unused capacity on the profit gap between the observed and the maximum profit when analysing international airline companies. As a result, they present a new ray economic capacity measure, which involves short-run profit maximisation, with the output mix held constant.

Pesonen (2001) demonstrates a design to profit procedure. The essential elements of this procedure are product business case calculations and profit consciousness of employees.

The theory of constraints (TOC) is introduced by Goldratt and Cox (1984). They claim that every real system such as a profit-making enterprise must have at least one constraint that prevents it from making more profits.

Efficiency calculation methods are widely used in the paper industry. Kleef et al. (2002) presents a financial model, which shows that for every 1 % decrease in downtime, profits increase by 4,7%...8,2%. In addition, they present a continuous process developed in downtime reduction. The main steps in this process are registration of failures, verification of downtime data, automatic analysis to create trend and prognosis graphs, and a structured approach to corrective action.

There are also other indirect measures and methods developed. Productivity (Boyd and McClelland 1999, Hannula 1999), reliability (Virtanen 2000), risk analysis (Henley and Kumamoto 2000, McCormick 1981), and cost function models (Fogelholm 2000) are examples of such methods and studies. In addition, life cycle cost (LCC) and life cycle profit (LCP) analyses are widely applied to investment profitability calculations Peltonen et al. (2002).

The existing methods and measures provide information, which can be successfully applied to web process improvements. Despite the fact these existing methods are inadequate: they do present only some of the cause and effect connections between the different factors and profit potentials. There are also interactions between the profit components, which are not described or formulated. In addition, the important systematic inspection of machine sections and functions, and related new technology potential effects are missing. The following research sub questions can not be fully answered applying the existing methods:

- What is the value of profit potential related to new technology applied to a web production process?
- From which factors, causes, machine section, function or device is the greatest profit potential coming from?
- Which profit potential components form the greatest profit potential?
- Which factor has the greatest effect on profit?
- What is the sensitivity of profit potential to different factors?
- What profit improvement possibilities does new technology optimised with raw material changes provide, and what is the greatest expected profit improvement impact?
- What is the effect of uncertainties on profit potential?

Due to the deficiencies of current studies, there is a clear need to develop a novel method.

1.3 Research problem

One problem is the formulation of connections between the causes and effects of profit potential components. Here, input variables should cover sources of all significant web process potentials. It is also important that the data needed for calculations is available. In other words: there should be such input variables, which are available from production and pilot web processes, simulations or other sources. Typically the needed data consists of prices, consumption amounts, efficiency figures and process related parameters.

Another problem is to try to understand and formulate the interactions between the profit potential components. Without considering the interactions, there can be misleading results i.e. emphasised or underestimated potentials.

A problem related to the existing process and profit optimisation methods is that by changing the process parameters, only some of the hidden potentials can be found. Therefore it is important to be able to simulate and optimise the effect of investment on a production line. Especially, changes of the investment and the effects on profit calculated over a time period should be included.

Sensitivity analyses and understanding of uncertainties and method limitations are needed when considering the accuracy and usability of the method and the calculated potentials. Finally, practical examples of method applications are a necessity to be able to present the usefulness of the method.

1.4 The aim of the research

The research problem has the above mentioned sub-problems, and the aim of the research is derived from these. The target of this study is to develop and present application of a new method for profit potential assessment and optimisation. The development of the method includes the following features:

- Formulation of the problem: the profit model.
- Formulation of different profit maximisation possibilities applying the current technology and new technologies.
- Sensitivity, uncertainties and limitations of potential assessment.
- Applications of the novel method.

1.5 Research methods and research steps

To be able to answer the previous mentioned research question, sub questions and the research problem, a constructive research approach, which is described in Kasanen et al. (1993), Lukka (2000), Labro and Tuomela (2003), is applied. In this work, research is carried out as described in figure 1.

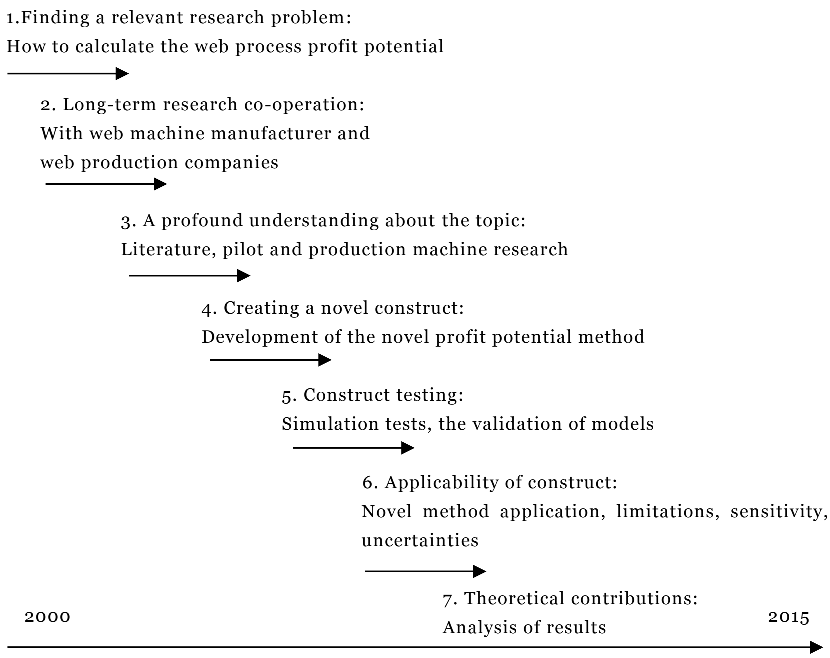


Figure 1. Research steps in this study.

The research started in 2000 after the finishing of previous study Pihko (2000). This previous study brought out potentials related to lost time in web production machines, but was not able to consider new technologies and the effect of the process on profit. However to be able to develop new products, it is crucial to be able to simulate how the new product or change in production line will affect the profit. This led to the definition of the research question and problem as described previously.

This study was highly supported by both a leading web production machine manufacturer and many web manufacturing companies, since they were interested in the subject: how and by which changes in production lines they could improve the profit most. This was a good basis for a long-term research co-operation, which was carried out during the years of 2000 to 2015.

A long-term research included testing of existing and new web machine components and concepts applying different raw materials, end products, and process parameters. The testing was carried out in different ways from simulations based on theories to the laboratory, pilot machine and finally production scale testing. This period where theory and practice were combined gave a profound understanding about the topic and also taught what type of method is needed to be able to calculate the profit potentials of web processes.

A literature study was carried out and completed many times during the research to find the currently available methods for profit potential calculations. The existing methods are presented and analysed in this work in relation to the research problem. The literature study is presented in details in Chapter 2. Chapter 2.4 describes how the existing literature studies cover part of the problem of how to define the profit potential.

A novel method is developed during this work applying the profit function definition, carrying out the production, pilot machine, and new product idea tests to form the web process profit model where novel technologies are included, formulating profit potential calculation equations, formulating sensitivity and uncertainty calculation equations, and through the iterations of these phases to further improve the calculation accuracy and applicability of the method. The novel method development is described in details in Chapter 3.

The novel method applicability is tested in Chapter 4, which concentrates on application of the novel method. There the novel method is applied to two different types of web production processes including also new technology components. The calculation of sensitivities and uncertainties is carried out to find out which possible limitations exist when applying the novel method. In Chapter 4.9 it is also considered how to apply the method to other types of products or processes.

Chapter 5 presents discussion where the results, research work, and contributions are analysed. In addition, there are recommendations based on the results presented.

1.6 Scope of the research

The dissertation approaches mainly web process technology related profit potentials. Web processes are continuous processes where different types of webs are typically produced at high production speeds. In this work the general web profit model can be applied to different types of webs although this dissertation focuses mainly on paper and board webs and processes.

Web process technology sets limits for production variables, and therefore applied technology has a strong effect on profit. There exist also potentials related to financing costs, labour costs, sales and marketing costs, rents etc. These potentials are partly discussed in this work, but the exact functions describing the connections of these and the profit is beyond the scope of this study and therefore not developed further in this dissertation.

The data presented in this dissertation is based on real production and pilot machine data. However, the names of the actual web process machines are not presented. This is due to the reason that the exact names are classified as confidential by the companies, which have provided the data.

1.7 Contribution

In relation to the existing scientific publications, this dissertation presents the first time the web process line profit model, where technology and driving related parameters, investments, prices and cost components which cover the total web production process are presented and can be changed annually in order to search for the best achievable profit. In addition to this, most of the models and parameters (see Appendix A) are new to the scientific community.

Further to this, the profit achieved in this new model is not limited (as e.g. in Coelli et al. (2001)) by the performance of the best practice companies but by the technology, price, cost component, and driving parameter limitations and by the nonlinear models limiting the performance. This is a significant difference between the known theoretical publications and the theoretical model presented in this dissertation. Applying this novel model it is possible to see the effect of a change of a single limitation, which can be related to technology or driving parameter or prices on the total profit achieved over the inspection period.

Further to previous, the novel method applies the new profit model in order to define the new optimisation levels of increasing complexity. These levels are applied to define the new profit potential concepts $\Pi_{\Delta,1...3}$ which are new to the scientific community. Coelli et al. (2001), Kleef et al. (2002), Hashemi et al. (2002), Koskinen (2008), and Färe and Primont (1995) have theories that can be applied to calculate part of these potentials, but since they don´t present the web process profit models, the parameters and their limitations needed for the calculations, and finally the profit potential definitions for the web processes, their theories can not be applied to calculate the profit potentials presented in this dissertation.

For a decision maker, it is important to understand the effect of changes in settings and technology on profit and the achieved profit potential. The comparison between the current manufacturing line and the other existing manufacturing lines does not provide decision maker the best achievable profit improvement possibilities, because new technology and optimal new technology settings are not taken into account.

The novel method is applied to new web process technologies. These technologies are new to the scientific community. In addition, applying the novel method to the new technologies there are parameter values, which are optimised to produce the greatest profit potentials. Based on these optimal parameter values, the optimal new technology solution together with sensitivity and uncertainty calculations is presented.

This novel method presents the cause and effect connections of factors, which form a profit potential related to certain function, machine section, and the applied technology. The method is tested and presented applying web production machine, pilot machine, and new idea related data.

The contribution of the novel method compared to the existing methods is:

1) This novel method presents new concrete concepts to evaluate profit potentials: different optimisation levels of increasing complexity are presented.
2) This novel method applies data not only from production machines, but also from pilot machines and other data sources thus providing possibilities to analyse new technology ideas applied to production lines.
3) This novel method provides description of improvement targets as web machine process component related input parameters. The effect of

input parameters on profit potential value is presented as currency units.
4) This novel method can be applied to evaluate the effect of simultaneous changes of many profit components: For example simultaneous changes in process component settings, different investments, prices etc. over a time period can be optimised. Investments are linked to their impact on process and cost components.
5) This novel method presents how to analyse sensitivity and uncertainties related to profit potentials.

This novel method provides data, which contributes to web process development and investments: compared to the existing methods, in applying the novel method machine development and investments can be directed more accurately based on the expected profit improvements.

This novel method can be applied to:

1) Focused investment and improvement actions planning and calculations.
2) Proactive product development planning.
3) Specified operation and service actions planning.
4) Comparison of web process technologies, machine concepts, or devices.

In addition, by generation of profit models describing other type of products, production systems, or services, it is possible to apply the presented method to other products, industries and markets.

2 THE EXISTING METHODS FOR PROFIT IMPROVEMENTS

Several studies have been carried out to establish different factors limiting the profit of a production unit. Some of these studies are considering directly profit improvement possibilities, but most are applying indirect measures of components, which have an effect on profit. The main theories and methods are presented here briefly.

2.1 Methods of applying profit measures

2.1.1 Distance function technique based profit decomposition

The distance function representation of a production technology is introduced by Shephard (1970). Later on, Shephard's theories are summarised and completed by Färe and Primont (1995), and discussed under profit maximising behaviour by Coelli (2002).

To describe an output distance function, the production technology of the firm is specified using the output set, **P**(**x**), which represents the set of all output vectors, $\mathbf{y} \in \Re_{+}^{M}$, which can be produced using the input vector, $\mathbf{x} \in \Re_{+}^{K}$. That is,

$$\mathbf{P}(\mathrm{x}) = \left\{ \mathbf{y} \in \Re_{+}^{M} : \mathbf{x}\ can\ produce\ \ \mathbf{y} \right\}. \qquad (1)$$

The output distance function is defined on the output set, **P**(**x**), as:

$$\mathrm{D_O}(\mathbf{x},\mathbf{y}) = \inf\{\theta : (\mathbf{y}/\theta) \in \mathbf{P}(\mathbf{x})\}. \qquad (2)$$

θ is the scalar distance by which the output vector can be deflated. The output distance function measure is the inverse of the factor by which the production output can be increased applying the same input level analysing a set of input and output vectors.

An input distance function considers how much the input vector can be proportionally reduced with the output vector hold fixed. Here, the input set **L**(**y**) represents the set of all input vectors $\mathbf{x} \in \Re_{+}^{K}$, which can produce the output vector, $\mathbf{y} \in \Re_{+}^{M}$. That is,

$$\mathbf{L}(\mathbf{y}) = \left\{ \mathbf{x} \in \Re_{+}^{K} : \mathbf{x}\ can\ produce\ \ \mathbf{y} \right\}. \qquad (3)$$

The input distance function is defined on the input set **L**(y), as:

$$\mathrm{D_I}(\mathbf{y},\mathbf{x}) = \sup\{\lambda : (\mathbf{x}/\lambda) \in \mathbf{L}(\mathbf{y})\}. \qquad (4)$$

1/λ is the relative scalar distance by which the input vector can be decreased. Hence $\mathrm{D_I}$ (**y**,**x**) ≥ 1 and $\mathrm{D_I}$ (**y**,**x**) = 1 defines the isoquant i.e. combinations of inputs that yield the same output. The best practice production units and their inputs define this isoquant and will have an efficiency measure i.e. distance function equal to 1. Those production units that lie inside the isoquant will have an efficiency measure less than 1.

Coelli et al. (2001) applies an output distance function to measure and decompose short-run profit efficiency of international airline companies. In order to limit possible inputs and outputs, they apply a linear program (LP), which is a slight variant of the long-run profit LP presented in Färe, Grosskopf and Lovell (1994).

They define the observed short run profits for a firm i, π_i, as:

$$\Pi_i = \mathbf{p}_i^{\mathrm{T}}\mathbf{y}_i - \mathbf{w}_{\mathrm{v}i}^{\mathrm{T}}\mathbf{x}_{\mathrm{v}i}, \qquad (5)$$

where $\mathbf{p}_i$ is the M×1 vector of output prices faced by the i-th firm, $\mathbf{w}_{\mathrm{v}i}$ is the K_v×1 vector of variable input prices faced by the i-th firm, $\mathbf{y}_i$ is the M×1 vector of outputs and $\mathbf{x}_{\mathrm{v}i}$ is the K_v×1 vector of variable inputs of the i-th firm. M is the number of outputs and K_v is the number of variable inputs.

The short-run maximum profit of each firm i is calculated as follows:

$$\underset{\mathbf{x}_{\mathrm{v}i},\mathbf{y}_i,\lambda_i}{\text{maximise}} \ \pi_i \qquad (6)$$

subject to

$$\begin{aligned} &\mathbf{Y}\boldsymbol{\lambda}_i \geq \mathbf{y}_i \\ &\mathbf{X}_v\boldsymbol{\lambda}_i \leq \mathbf{x}_{vi} \\ &\mathbf{X}_f\boldsymbol{\lambda}_i \leq \mathbf{x}_{fi} \\ &\mathbf{N1}^T\boldsymbol{\lambda}_i = 1, \end{aligned}$$

where M×N matrix $\mathbf{Y}$, K_v×N matrix $\mathbf{X}_v$, K_f×N matrix $\mathbf{X}_f$ consists of column vectors $\mathbf{y}_i$, $\mathbf{x}_{\mathrm{v}i}$, and $\mathbf{x}_{\mathrm{f}i}$ respectively for all N firms. $\mathbf{x}_{\mathrm{f}i}$ is the K_f×1 vector of fixed inputs of the i-th firm. K_f is the number of fixed inputs. λ_i is the N×1 vector of weights of the i-th firm. **N1** is the N×1 vector of ones.

The above-mentioned linear program provides maximal profit applying weighted mean input and output values of reference firms i.e. international airline companies. The weighting factors are limited so that the weighted mean value of the fixed inputs of reference firms is not greater than the fixed inputs of the target (optimised) firm.

For profit potential decomposition, Coelli et al. (2001) proposes the following:

$$\begin{aligned} (\Pi^* - \Pi) &= (\Pi^* - \Pi^{\mathrm{rec}}) + (\Pi^{\mathrm{rec}} - \Pi) \qquad (7) \\ &= [\mathbf{p}^{\mathrm{T}}(\mathbf{y}^* - \mathbf{y}^{\mathrm{rec}}) - \mathbf{w}_{\mathrm{v}}^{\mathrm{T}}(\mathbf{x}_{\mathrm{v}}^* - \mathbf{x}_{\mathrm{v}}^{\mathrm{rec}})] + \\ &\mathbf{p}^{\mathrm{T}}(\mathbf{y}^{\mathrm{rec}} - \mathbf{y}) - \mathbf{w}_{\mathrm{v}}^{\mathrm{T}}(\mathbf{x}_{\mathrm{v}}^{\mathrm{rec}} - \mathbf{x}_{\mathrm{v}})], \end{aligned}$$

where * refers to a solution of equation (6), a vector which provides maximum short run profit. rec refers to the ray economic capacity of a plant. The quantity of ray economic capacity is the vector of output at the point of maximum short run profit, using the given production technology, **P**(x), and the fixed input vector, $\mathbf{x}_{\mathrm{f}}$, when the variable input vector, $\mathbf{x}_{\mathrm{v}}$, may take any non-negative value and the output mix (but not the level) of the original production point must be preserved.

The distance function approach can be applied to profit efficiency comparisons of production units. However, for profit potential assessment, the method can be applied only partially due to the following shortcomings:

1) The potential value is limited by the performance of the best practice units i.e. results are only relative to other units in the sample (see equation (6)).
2) The potential measures are general and they do not provide information about where and how significant is the potential related to different sections and components of a production unit (see equation (7)). Thus it is difficult to conclude what should be improved applying these methods.

2.1.2 Life cycle profit models

Peltonen et al. (2002) present **a tool for life cycle cost (LCC) and life cycle profit (LCP) analysis.** The LCC/LCP analysis is a systematic approach aimed at calculating the costs, profits and profitability of an investment over its entire life span. Matilainen (2005) applies the LCC/LCP analysis to paper machine press section investment, and presents a model suitable for press section concept selection.

Koskinen (2008) developed a model,

$$pf(z)-w \cdot z, \qquad (8)$$

where p refers to paper sales price, f(z) production function, w input price vector, and z input levels of different input parameters z_i (fixed costs, energy, raw materials, consumed parts, maintenance, technology, expertise). Input parameters z_i have the dimensions e_i (efficiency), and w_i (cost). Efficiency values range in an interval of (0,1), with higher values referring to a better level of input. Different contracting strategies change efficiency and cost values and therefore production line life cycle profit changes according to the calculation model.

The model is validated applying empirical data from several paper production lines. Based on this validation, the model can be used in paper production line life cycle profit calculations to a high degree of accuracy. However, for assessment of process changes on production line profits, a more specified model, which includes dependencies between important process input parameters and profits, is needed.

Rosqvist (2001) applies LCP-model and presents a risk index, RI, defined as:

$$RI = 1-E[H(f((X))], \qquad (9)$$

where E refers to expectation of the life cycle profit, and H is Heaveside step function, which measures the probability of the random scalar function f not exceeding a threshold value of zero. Usually f(X)=Z, where Z is life cycle profit measured as the net present value. X is a random vector of life cycle profit criteria or attributes (cash flows and costs). A decision rule RI $\leq \alpha$, where α is a risk criterion e.g. α=0.05, is applied to measure the adequacy of LCP-assessment.

This method presents simple rules $E[Z] \geq 0$ and $RI \leq \alpha$ -> accept the investment option. However, the method requires a great amount of data and expertise to produce reliable distributions of variables Z and RI. Therefore risks related to investments are more often considered by applying return requirement related to risk level. Diesen (1998) presents basic rules for this procedure.

2.1.3 Design to profit method

The design to profit procedure (Pesonen 2001) is a proactive mind set or thinking pattern.

The essential elements of this procedure are product business case calculations and profit consciousness of employees. The calculation is based on product future sales revenues and life-cycle costs estimation. Future sales are estimated over product life-cycle, which can be several years depending on the product. For the most important variables affecting the profit, the method applies the following formulas:

$$S_{netsales} = S_{grsales} - E_{adjustments}, \qquad (10)$$

where $S_{grsales}$ is gross sales and $E_{adjustments}$ is adjustment expenses.

$$E_{mat}(f) = \sum_{i=1}^{N} C_{salespack}(f)\, V_{mc}(f), \qquad (11)$$

where $E_{mat}(f)$ is the material expenses of N different sales packs assembled in the factory f (factory f refers mainly to a cellular phone manufacturing unit), $C_{salespack}(f)$ is the cost of a sales pack produced in factory f, and $V_{mc}(f)$ is the manufacturing volume of the sales pack in factory f.

$$E_{mc}(f) = [C_{smd}(f)\, N_{smd}(i) + C_{rob}(f)\, T_{rob}(i) + C_{test}(f)\, T_{test}(i) + C_{gen}(i)]\, V_{mc}(f), \qquad (12)$$

where $E_{mc}(f)$ is manufacturing expenses at factory, $C_{smd}(f)$ is a surface mounting device cost per component, $N_{smd}(i)$ is the number of SMD components of part i, $C_{rob}(f)$ is automatic assembly cost per minute, $T_{rob}(i)$ is automatic assembly time of part i, $C_{test}(f)$ is testing cost per minute, $T_{test}(i)$ is testing time of part i, and $C_{gen}(i)$ is a plant-specific general cost per part (i).

$$E_{sm}(j) = p_{sm}(j)\, V_{sales}(j), \qquad (13)$$

where $E_{sm}(j)$ is sales and marketing expenses in region j, $p_{sm}(j)$ is an adaptive global parameter in region j, and $V_{sales}(j)$ is a corresponding sales volume.

For manufacturing costs calculation, design to profit method applies a model named SMILE (Simulation of Manufacturing and Logistics

Expenses). The contribution of the model is to calculate a product manufacturing cost estimate and the trade-offs between alternative ways of building the features of the product. Smile balances manufacturing in order to maximise production capacity with minimum total production costs.

The method offers a frame for estimating and calculating future profit because it makes the revenues and expenses visible in the long term and across the organisational boundaries. However, for web process profit potential assessment, the method can be applied only partially, because:

1) The method concentrates on the design phase of a product, which is after the profit potential definition phase.
2) The profit components are developed for the telecommunication industry.
3) The profit potentials related to production are considered only for mobile phones manufacturing applying SMILE.

2.1.4 Theory of constraints procedure

The theory of constraints (TOC) is introduced by Goldratt and Cox (1984), and further developed by Goldratt (1990), and analysed from a practical viewpoint by Noreen et al. (1995). The idea in TOC is that every real system such as a profit-making enterprise must have at least one constraint that prevents it from making more profits. In TOC, profits are measured by throughput less operating expenses. Throughput is defined as the rate at which the system generates money (i.e., incremental cash flows) through sales. The simplified version of throughput is revenue less direct materials. Operating expenses are all the money the system spends in turning inventory into throughput.

The general TOC process applies the following procedure (Goldratt 1990):

1) Identify the system's constraints.
2) Decide how to exploit the system's constraints.
3) Subordinate everything to the above decision.
4) Elevate the system's constraints.
5) If in the previous steps a constraint has been broken, go back to step 1), but do not allow inertia to cause a system constraint.

The strength of TOC is that it concentrates on continuous improvement of bottlenecks. For example, the key statistic in TOC, contribution margin per unit of the constrained resource, provides valuable information for continuous profit improvement planning. For profit potential assessment purposes, the weakness of TOC is related to the step number 1) Identify the system's constraints:

1) Profit potential components related to constraints (which form improvement possibilities) are not identified accurately enough to be able to understand where and from which components is the greatest profit potential composed of. This information is essential to be able to justify decisions related to improvements.
2) The point of view in TOC is mainly continuous improvement of the existing production unit where improvement is largely based on

rearrangement of existing resources. The great potential implications related to new technologies are not considered. There are, for example, possibilities to change many bottlenecks at the same time.

2.1.5 Value creation and profit optimisation

Winther (2003) presents a framework for evaluating and optimising profits in a business operation. This framework applies the following:

Profit = Price – Cost , (14)

Price = Market Power * (Value / Risk) * Pricing Decision Factor, (15)

where Market Power * (Value / Risk) reflects the theoretical highest market price available, and Pricing Decision Factor is a measure for how much below that price the seller is actually selling the product. Market power has a value between 0…1 and is estimated based on analysed market data. If there is no competition, market power can reach a value close to 1. Market power depicts the ability to raise the market price of a product or service over marginal cost. Typically there also exist customers to whom a company will sell their products at the price lower than a fixed list price. Then Pricing Decision Factor, which has a value between 0…1, has a value less than 1. The optimal profit is found as a function of volume, value drivers and the other parameters.

This theoretical framework considers the effect of product volumes, value drivers, and the other parameters on profit. However, the production unit is not examined further and therefore not optimised.

2.2 Methods of applying indirect measures

2.2.1 Efficiency calculation

There are various versions of efficiency calculation methods presented in literature and applied in the paper industry. Here are generally accepted methods, and some new proposals described.

Overall equipment effectiveness (OEE) is related to Japanese total productive maintenance (TPM) presented in Nakajima (1988). According to Samuel et al. (2002), and Ahuja and Khamba (2008), a widely applied OEE definition for productivity measurement in manufacturing operations is:

OEE = A*P*R (16)

where

A = Availability = ((Loading time – Down time) / Loading time)*100,
P = Performance efficiency = ((Processed amount) / (Operating time/Theoretical cycle time))*100,

R = Rate of quality = ((Processed amount – Defect amount) / Processed amount)*100.

Idhammar (1997) presents OEE definition for paper machines:

$$A = \frac{Uptime}{Uptime + Downtime}, \tag{17}$$

$$S = \frac{Actual\ Speed}{Actual\ Speed + Slowdown}, \tag{18}$$

$$Q = \frac{\Pr ime\ Quality\ Volume}{\Pr ime\ Quality\ Volume + Reject}, \tag{19}$$

where

A = Availability,
S = Speed,
Q = Quality.

Overall equipment performance efficiency is calculated by multiplying the three factors:

$$OEE = A*S*Q. \tag{20}$$

Idhammar (1997 and 2002) presents an estimate of improvement potential as saving opportunity in increased reliability related to OEE. In addition, Idhammar (1996) proposes that the life-cycle costs (LCC) and life-cycle profits (LCP) concepts should be adopted in a company management approach to optimise the use of assets. Despite the presented ideas, Idhammar does not expand on these estimations nor present data or equations needed for optimisation.

The **traditional efficiency calculation** is widely in use at paper mills. The calculation is carried out according to Sipilä (1986) as follows:

$$\eta_{total} = \eta_{time}\ \eta_{quantitative} = \eta_1\ \eta_2\ \eta_3\ \eta_4, \tag{21}$$

where

η_{total} = Total efficiency,
η_{time} = Time efficiency = $\eta_1\ \eta_2$,
$\eta_{quantitative}$ = Quantitative efficiency = $\eta_3\ \eta_4$,
η_1 = Operation efficiency = Paper machine operation time / theoretical operation time (shutdown time counted),
η_2 = Machine efficiency = Paper machine productive operation time / total operation time (break time counted),
η_3 = Trim efficiency = Paper web net width / maximum web width (trim broke counted),
η_4 = Production efficiency = Packed net production / gross production at reel (broke counted).

The **average value calculation** method is originated from the German paper industry standard (1982):

$$\eta_{total} = \eta_{time}\,\eta_{quantitative} = \frac{t_p\, q_p}{t_o\, q_t}, \qquad (22)$$

where

t_p = Production time (time that web is on reel),
t_o = Operation time (calendar time – shutdowns),
q_p = Packed production,
q_t = Theoretical or calculated production.

Net efficiency (N_{eff}) calculation is defined as follows (Kuhasalo et al. 2000):

$$N_{eff} = G_{eff}\, P_{eff} \qquad (23)$$

where

G_{eff} = Gross efficiency (24)
= Production time / Maximum time available,
P_{eff} = Production efficiency
= Saleable paper / Gross production. (25)

Production time is the time the sheet is reeled.

According to Mardon et al. (1998), there are three definitions of machine efficiency: **Absolute (A_{eff}), Time (T_{eff}) and Operating (O_{eff})**.

A_{eff} = Saleable paper actually produced / (26)
Saleable paper that could have been produced
at the actual running speed and in the total time
that the mill was available,
T_{eff} = Time available to make paper / (27)
Total time,
O_{eff} = Paper made / Paper that could have (28)
been made in the time available.

From these definitions,

$$A_{eff} = T_{eff}\, O_{eff}. \qquad (29)$$

Lost efficiency is the difference between 100% absolute efficiency and actual absolute machine efficiency. Mardon et al. (1991) present speed and efficiency trends and a rough estimation of the cost of the lost efficiency. In addition, they present start-up curves from production machines. These curves clearly illustrate, that there are great losses during the first two or three years due to low speed and efficiency.

The **efficiency number (EN)**, which considers the area produced per one meter width per day is defined as follows:

$$EN = N_{eff}\, v\, c \qquad (30)$$

where

v = paper machine speed [m/min],

c= unit conversion factor = 24 * 60 / 10^6 [$\frac{\min}{d}\frac{km^2}{m^2}$].

The traditional efficiency calculation does not take into account the paper quality or the possibility to produce paper even more. This is the reason why an ASQP model is developed (Kaunisto 2000).

The **ASQP-model** calculation is defined as follows:

$$p_{capable} = p_{max} * A * S * Q * P, \quad (31)$$

where

$p_{capable}$ = Production volume, that a paper mill is capable of producing,
p_{max} = Maximum production volume, which can be produced by utilizing the theoretical or potential maximum capacity of the papermaking line,
A = Availability = Production time / Theoretical maximum production time (shutdown time costs counted),
S = Speed efficiency = Production speed / Theoretical maximum production speed (average of three minimum 6 hours trouble-free production speed counted) (decreased speed costs counted),
Q = Quality efficiency = Produced paper grade contribution margin / Theoretical maximum produced paper contribution margin (decreased quality costs counted),
P = Production quantitative efficiency (Contribution margin efficiency) = (Contribution margin of the production delivered to customers – Broke costs due to lost raw materials and energy) / Potential contribution margin (break and broke costs counted).

Kleef et al. (2002) presents a **financial model** where every 1 % decrease in downtime leads to profits increase by 4,7%...8,2%. In addition, they present a **continuous process developed to downtime reduction**. The main steps in this process are: registration of failures, verification of downtime data, automatic analysis to create trend and prognosis graphs and a structured approach to corrective action.

A little effort to describe the connections between efficiency, speed, grade mix, and profitability is presented by Smook (1986). This description points out, that there is an optimum speed and basis weight range, which produces the best profitability. However, there are no equations related to these connections presented.

It is important to analyse efficiency factors and improve efficiency continuously in order to be able to achieve a high performance and profitability level of a web process line. However, in order to be able to carry out a more accurate efficiency analyses in the future, there is a need to clarify and standardise the efficiency calculation applied in different paper mills. Airola and Bescherer (2004), and Airola et al. (2005) present efforts to clarify the calculation. The latest version of calculation indices is presented by PI and Zellcheming (2005).

One should remember that efficiency is only one factor of profit potential. In addition, it is not enough to consider the potential at a paper mill (for example the design speed or quality as a reference speed or quality), but also the potential that can be achieved through improvements in equipment, operations, and furnish.

2.2.2 Cost and profitability calculations

Fogelholm (2000) presents that cost functions in paper production require sufficiently accurate nonlinear and multivariable based allocation parameters. These cost functions are required for **cost models**, which can be applied to product costing, material budgeting, and simulation calculations. Fogelholm and Hämäläinen (2004) present a **program**, which can be applied to **budgeting and sensitivity analysis calculations of cost components**.

A **cost and profitability model** and simulator were developed by Dietrich (2002). The developed tools can be used in training or support for decision making at different mill levels.

Almi (2002) developed an **investment calculation model**. The model can be applied to assessing investment value to a paper producer. The accuracy of the calculation can be further improved by a systematic data collection together with a paper producer. In addition, a life cycle costs study would improve the accuracy of the model.

For **momentary papermaking line profitability analysis**, Kaartoluoma and Pietilä (2004) have developed a program. Based on paper grade specific default values, the program presents target for profitability, and the current profitability. In addition, it is possible to carry out profitability comparisons between different paper grades and paper machine settings.

Diesen (1998) presents two important key figures to evaluate the profitability criteria for investments: The **Pay Back (PB)** and the **Internal Rate of Return (IRR**). The third widely applied method is the **Net Present Value** (**NPV**) calculation. Liljeblom and Vaihekoski (2004) have studied that PB, IRR, and NPV are the most commonly used methods in Finnish publicly listed companies. Brealey and Mayers (2000) present a comprehensive discussion on benefits and disadvantages related to different methods.

Pay back period = Additional new revenues or cost savings / Investment, (32)

IRR (%) = The discount rate that equates the present value of the future annual cash flows to the initial investment,
Initial investment = Total investment at time of investment decision.

$$\text{NPV}= C_0 + \sum_{t=1}^{n} \frac{C_t}{\left(1+r_t\right)^t}, \qquad (33)$$

where

C_o = Investment first cash flow (Acquisition cost),
r_t = Rate of interest,
n = Lifetime of investment,
C_t = Investment net cash flow during year t.

The following rules of thumb exist: With small improvements or rebuilds, due to risk factors caused by some machinery remaining in its old form, the pay back time should be less than 3...4 years or IRR > 25 %. Typically small improvements are targeted to improve performance of one critical bottleneck of a production line. However, after this small improvement is implemented, there will be several new unexpected bottlenecks limiting the production. Therefore pay back period related to small improvements should be short enough. With large paper machine projects, where all components are new and they are dimensioned to new high production level, IRR > 13 % is a rough guideline according to Diesen (1998).

The above-mentioned cost and profitability calculation methods and models can be applied to trendsetting profitability and cost analyses. However, in order to be able to analyse and optimise profit improvement possibilities related to web process components and variables, and cause and effect connections between the variables, a more specified procedure is needed.

2.3 Other methods and studies

2.3.1 Papermaking line process optimisation

Madetoja (2007), and Madetoja and Tarvainen (2008) present a method for multiobjective papermaking process line optimisation. A multiobjective approach is also applied by Linnala and Hämäläinen (2011) for process design of the broke system in which both operation and design are optimised. According to Madetoja and Tarvainen (2008), the process line model is denoted by:

$$\begin{cases} A_1(p_1, q_1) = 0 \\ A_2(p_2, q_1, q_2) = 0 \\ \vdots \\ A_{nm}(p_{nm}, q_1, \ldots, q_{nm}) = 0, \end{cases} \qquad (34)$$

where A_i for all i = 1, . . . ,nm stands for the i-th unit process models, $p_i \in \Re^{li}$ denotes a vector of the inputs, and $q_i \in \Re^{ki}$ is a vector of the outputs (model states) for the i-th unit process model A_i. For two paper quality targets (the tensile strength ratio and the formation) optimisation under uncertainty, the following is presented:

$$\min_x \left\{ \max_{i=1,\ldots,4} \{ f_i(x, q_1, q_2) \} + \rho \sum_{j=1}^{2} \omega_j f_j(x, q_1, q_2) \right\}, \qquad (35)$$

where x is a vector of paper machine control variables, f_1 and f_2 are objective functions that measure the distance between the result calculated using process models and the target, f_3 and f_4 are objective functions that measure the distance between process model uncertainty and uncertainty allowed, ρ is a scalar, and ω_i are the weighting coefficients defined by user. Weighting coefficients can be applied when one quality target is more important than the other. Optimisation is continued until both quality and reliability targets defined by user are fulfilled.

The presented approach for process line optimisation can be applied to multiobjective optimisation. In these cases, there are typically many different quality targets, which should be achieved by changing web process control variables. Then this approach can be used as a tool to achieve these targets. One challenge that exists is how to define appropriate objective functions for the unit process and process uncertainties. The quality data collected to produce process models for quality may not be applicable to other type of furnish and paper quality. Therefore applicability of this optimisation approach is probably limited to very similar process conditions i.e. the same type of process machine components and raw materials as used to define the process models. By analysing the installed web processes and their raw materials, one can find out that there rarely exist web process lines with exactly the same kind of process.

For profit maximisation purposes, multiobjective optimisation is not required since the target is to maximise profits. When maximising profits, quality can be included into a model and connected to product price. Then maximising quality does not necessarily maximise profits. On the other hand, effects of uncertainties related to for example raw material and product prices can be taken into account by calculating different scenarios i.e. by changing input parameters, for example raw material and different quality product prices according to forecasted price scenarios.

2.3.2 Productivity measurement

Productivity is generally defined as output divided by input. At company level the inputs are usually divided into the following groups: labour, capital, materials, energy, and miscellaneous.

Boyd and McClelland (1999) utilise a flexible measure of productivity that includes environmental performance. They apply an input distance function and develop an expanded distance function to measure the ability of integrated paper plant to expand desirable output and contract undesirable output at the same rate with a given set of inputs. The potentials studied are related to paper industry input use and pollution output amounts, and production losses due to environmental constraints. In addition, the potential for improvements that increase productivity and reduce pollution is assessed.

Most productivity measures used in industry are partial productivity ratios. Hannula (1999 and 2002) presents total productivity measurement, which is based on relative simple and commonly used partial productivity ratios. The relative change in total productivity is expressed as a function of the relative changes in the partial productivity ratios and the cost structure of a firm in the base period as:

$$\Delta P_T = \frac{1}{\sum (C_{i_{base}} / C_{T_{base}} \cdot 1/(\Delta P_i + 1))} - 1, \qquad (36)$$

where

ΔP_T = Relative change in total productivity,
$C_{T_{base}}$ = Total costs in base period,
$C_{i_{base}}$ = Costs of the input i in the base period,
ΔP_i = Relative change in the partial productivity of input i.

The interaction between productivity and profit is described by Loggerenberg and Cucchiaro (1982). They illustrate that change in resource or product quantity causes change in productivity and through changes in costs and revenues, change in profit. However, connection between productivity and profits is not straightforward: productivity improvements are not leading automatically to increased profits especially when the sales price and volumes of products produced are low. According to Eloranta and Holmström (1998), instead of concentrating on classical productivity, efficiency analysis based on value added and cost of resources consumed is appropriate when the issue is industrial competitiveness.

Fogelholm (2006) describes productivity improvement stages in mills. Productivity improvement is a very important continuous process especially due to the recent development of increasing raw material prices and decreasing paper prices.

2.3.3 Reliability methods

Virtanen (2000), and Virtanen and Hagmark (1997, 1998) have developed a new **method for machine design** in which the operational reliability of the product was calculated and compared with the need for reliability of the end-user based on his or her reliability priorities. This method and the developed software program are very comprehensive way to design and simulate the operational reliability of the product. The method can be applied to advanced and complex systems, which are very dependent on a high reliability level. This method is targeting to profit improvement from one viewpoint – design of the product to maximise reliability i.e. to minimise unplanned shutdowns, which limit production and profits.

There are other quantitative and qualitative reliability analysis methods like **RCM** (Reliability Centred Maintenance) methodology including **FMECA** (Failure Mode Effect and Criticality Analysis), **HAZOP** (Hazard and Operability study), **HEA** (Human Error Analysis), **ETA** (Event Tree Analysis), and **FTA** (Fault Tree Analysis). A great effort to study these methods and to develop new ones was carried out in Finland in 1996-2000. During these years a national competitive reliability programme produced new techniques, methods and tools for control of reliability. (Holmberg 2001)

Applying reliability methods it is possible to estimate at the design or operation phase of the product the causes and effects and probability of different faults or operation deviations. The shortcoming with these methods with respect to profit assessments is that there is in many cases a great amount of analysis work, and still little information, which can be applied to profit improvements. When the limiting factors (improvement potentials) have been analysed, and there is clearly a problem relating to reliability of some function, then these methods are appropriate tools.

2.3.4 Risk analysis methods

The basic definition of risk of an undesired event is according to McCormick (1981):

$$R_k = F\,D^k, \qquad (37)$$

where

R_k = Risk,
F = Expected frequency of occurence,
D = Expected damage (cost, value),
k = Weighting exponent, $k > 1$, when big losses are emphasised.

According to Chapman and Ward (1997), a broad definition of project risk is the implications of the existence of significant uncertainty about the level of the project performance achievable. A source of risk is any factor that can affect project performance, and risk arises when this effect is both uncertain and significant in its impact on project performance. Whatever the underlying performance objectives, the focus on project success and uncertainty about achieving it leads to risk being defined in terms of a threat to success.

The essential purpose of risk management is to improve project performance via systematic identification, appraisal and management of project-related risks. The roots of project uncertainty are associated with six basic questions which need to be addressed (Chapman and Ward 1997):

1) Who are the parties ultimately involved? (Parties)
2) What do the parties want to achieve? (Motives)
3) What is it the parties are interested in? (Design)
4) How is it to be achieved? (Activities)
5) What resources are required? (Resources)
6) When does it have to be done? (Timetable)

According to Henley and Kumamoto (2000) and McCormick (1981), the major tasks of probabilistic risk assessment (PRA) are:

1) To define the type of accidents that can occur and their frequency of occurrence.

2) To quantify the consequences of each event.

It is important to identify key risks (threats to success), preventive actions, and persons in charge early enough, in order to achieve the target: an economically profitable web process.

The weakness of the **risk analysis method** is that it directs the attention to risks and not so much towards possibilities and potentials. When assessing profit potential it is important to consider both potential related to risks (losses), and potential related to possibilities (new actions, technology etc).

2.3.4 Trouble shooting method

Kepner and Tregoe (1997) developed the **ATS (Analytic Trouble Shooting) method** from watching and working with people who are good at solving problems. ATS is about finding the true cause of the problem, and selecting a fix which works the best way to help avoid future problems.

This method is appropriate, when there is a problem, which can be solved using the cause and action method. With web processes, there are many problems that can be solved applying this method. However, when there is a need to identify the improvement potential related to profit, this method is not a powerful tool.

2.3.5 Product development method

The product development method (Ulrich and Eppinger 1995) contains the following steps:

1) Product development project start-up, key person and resources selection.
2) Customer need identification.
3) Product specifications to fulfill the customer needs.
4) Concept generation.
5) Concept selection.
6) Concept development ready for manufacturing, manufacture and assembly costs reduction development.
7) Prototype making and testing.
8) Product selling and manufacturing, customer feedback and further development.
9) Product development project analysis.

An important part of product development is customer need identification. Product development applies several methods to carry out this identification task. To be able to understand the order of importance of customer needs, a paired comparison method called **Analytic Hierarchy Process** developed by Saaty (1994), is widely applied. To be able to consider relations between customer and product characteristics, a method called **Quality Function Deployment (QFD)**, developed by Akao (1994), is commonly applied. To assess the customer value, Lindstedt and Burenius (1999) present the following definition:

Customer value = Experienced benefit / Total costs, (38)

where

Experienced benefit = The benefit, which customer experiences from the product,
Total costs = All the costs caused by the product (acquisition and operating costs).

It is not enough to be able to understand customer needs and to develop suitable product(s). Deck (2003) points out that due to limited resources **portfolio management** is needed to be able to create new successful products efficiently.

The product development method presents phases, which should be taken into consideration when developing a new product. However, considering web processes, the development steps from 1 to 7 have been mostly carried out for many decades, and nowadays step 8 is the most current.

The product development process should not be started until customer requirements are defined, otherwise there will be a waste of resources. However, the tools, which product development process applies, are not adequate to direct the product development towards that direction where the potential i.e. profit improvement possibility is the greatest. Therefore, the profit potential assessment process is required to be developed to guide the product development process.

2.3.6 Paper machine studies

Juppi (2001) studies the functioning of a new vacuum roll construction by means of **experiments and simulations** up to a speed of 2400 m/min (40 m/s). As a conclusion of the study, the new vacuum roll with chambers offers a possible means of web control at very high machine speeds. This study presents, that potentials of new web process components can be discovered by experiments and simulations before production machine applications. In addition, uncertainty related to new technology can be reduced by applying test methods suitable for the certain component.

It is important to find new potentials, which do not exist in production machines. In this way, there can be significant profit improvements available in the future by investing in new technology. Therefore, it is important to be able to assess in early phases of product development the profit potentials related to new technology applications.

Ahola (2005) studies process measurements from the paper machine and developed an application for the evaluation of web break sensitivity in a paper machine. **A web break sensitivity indicator** was built using the basic principles of case-based reasoning with a linguistic equations approach and basic fuzzy logic. The indicator combines on-line measurement data with expert knowledge and provides a continuous indication of break sensitivity. Web break sensitivity defines the current operating situation at the paper mill and provides new information to operators. Web break sensitivity is presented as a continuous signal with information about actual web breaks depicted as an eight-hour trend. The trend shows how the situation has developed and the current value gives a prediction for the next 24 hours if the situation remains constant. Together with information about the most important variables, this prediction gives operators enough time to react to the changing operating situation.

Ahola (2005) discovers that broke and pulp feeds in addition to pH measurements are the most important process variables in describing sensitivity levels for web breaks. However, despite the fact that a paper producer recognises that increasing the amount of broke increases the number of breaks, this variable can not necessarily be changed especially when the wet broke storages are full.

In addition to the fact that it is important to optimise the process variables to ensure a good runnability, greater positive changes to runnability and profitability of a web process line can be achieved by studying how to change the web process technology. The web process technology can be improved by: an increase in web dryness after press section, a decrease in wet web draws, and a decrease in unsupported web transfers. These improvements would produce a good runnability level even if the furnish is not the best possible due to not optimised process variables.

Saarela (1998) studies the operation reliability of board machines. As a result, concrete improvements and improvement proposals are presented. During the year when the study was completed, web breaks on the machine were reduced significantly mainly due to **web break analysis**, improved machine cleaning and fabric change optimisation. The machine speed increased at the same time. Also the efficiency characteristics improved. It is important that there has been emphasis in this study on continuous improvements and motivation of personnel. In this way, there will probably be a likelihood of longer lasting results than without this aspect.

Saarela (1998) thesis is very much a down-to-earth study. There are specific problems, and there is a good analysis of these problems. On the basis of the analysis, there are appropriate improvement proposals, which are partly carried out during the study. This leads to good results. Saarela (1998) thesis received an award. This award was proposed by paper machine specialists in Finland. From a profit improvement standpoint, this thesis presents ways to improve board machine profit by improving analysis at the mill.

Luumi (2002) focuses on defining online fine paper machine runnability problems in order to be able to increase the efficiency of the fine paper web process line. During the study, a good literature review of different factors affecting runnability of the paper machine and quality of paper is carried out. In addition, there are three intensive monitoring periods, when accurate definitions of the causes of breaks and broke are explored. As a result, the reasons behind runnability problems are mainly due to base paper defects. The consequence of the monitoring was that there is a more accurate definition of roll protection limits developed.

Luumi (2002) presents ways to improve paper machine performance by carefully **analysing lost production causes**, and **optimising paper machine operation** on the basis of these results. This kind of analysis and optimisation will likely lead to improved performance in the future, if carried out regularly.

Pihko (2000) defines the reliability of paper machine forming and press sections by collecting and analysing data from four production machines. There are also the consequences of insufficient reliability described as damages and risks. **On the basis of the causes and effects for insufficient reliability, the most important targets for development are identified**. A more precise study is carried out in two development cases: The high vacuum suction box and the steam box are analysed in more detail in order to develop their reliability.

The **data collection and analysis** presented in Pihko (2000) is very important, because in this way it is possible to identify the significance of the lost production caused by different functions and parts of the web production process. This directs required actions where they are needed most. The other important point of view is that the analysed data improves product development of web processes, and this leads to improved web process performance from the start-up of the new web process line, which means great savings to a web producer compared to improvements performed later during the operation.

Hashemi et al. (2002) study the effect of changes in the press section on paper machine performance. This study applies **an integrated pressing-drying simulation** together with data from a fine paper machine in order to compare the effect of a press section steam box, an extended nip press, and changes in dryer section steam pressure on paper machine speed and economy. On the basis of simulation results, an extended nip combined with a steam box is the most profitable solution measured as payback time.

Hashemi et al. (2002) study presents that investment in press section water removal capacity is more profitable than an increase in dryer section steam pressure. However, this study neglects a number of important variables such as speed and breaks connections, efficiency changes, energy consumption changes etc.

Heikkilä (1993) carries out a thorough study of the drying process. He presents the basis for **drying simulation models**, which are applied broadly in different drying process simulations.

Treppe, Dixit, and Kuitunen (2011) develop **a balance model of the drying process** to identify and capture the energy saving potential. The model is applied in three paper mills to define the areas, where the greatest energy savings and shortest payback periods can be found.

Paakki (2009) studies **PCC production in connection with paper machine applying exhaust CO_2 gas available from paper machine processes**. Paakki develops **a profitability model** where the size of the PCC production unit and concentration of CO_2 have a great impact on profitability.

All of the above presented studies are targeted to improve certain parts of a web process. However, the whole web process, totally new technological concepts applied to web processes, and the important relations between the different web process components and the profit are only partially analysed in these studies.

2.4 The existing methods, the research target, and the ideal method

The above presented methods cover part of the research problem since they present ways to calculate profitability, profit, efficiency, reliability, process, and risks from different viewpoints. The ideal method to calculate the profit potential would cover all the viewpoints and all the details to be able to form an exact description of the profit potential. However, the ideal method would be very complex and difficult to apply. The target of this work is to develop a method which covers, to a large extent, the factors affecting profit potential but which is still simple enough to apply.

Figure 2 presents theoretically the main existing methods, the target of this research, and the ideal method. The horizontal axis Details describes how accurately or in depth details/factors affecting the profit potential are described in this method. The vertical axis Coverage describes how comprehensive or limited this method is in describing the total profit potential.

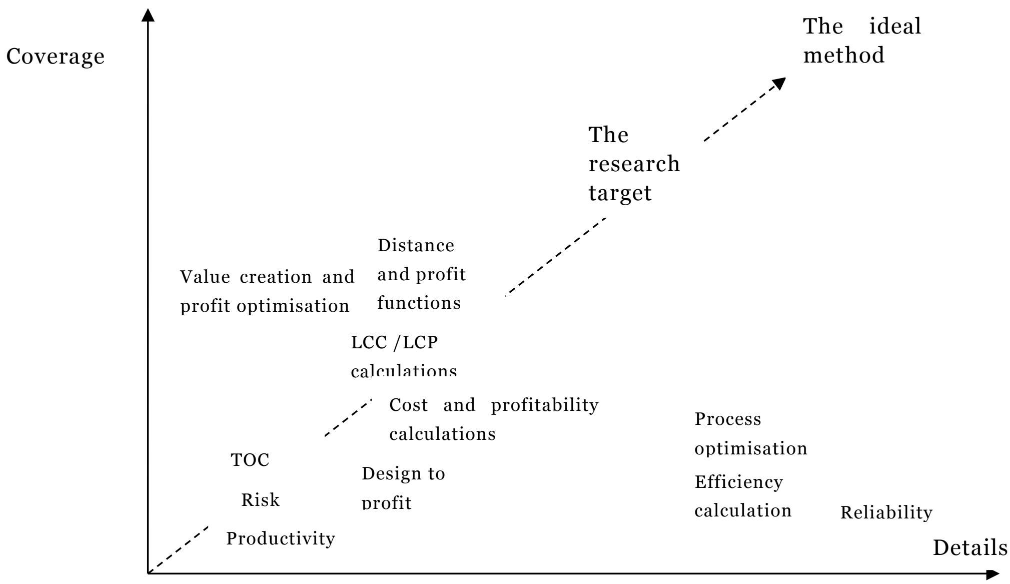


Figure 2. The existing methods, the research target, and the ideal method.

3 NOVEL METHOD DEVELOPMENT

The development of the novel profit potential calculation method is described in this chapter. In addition to the method development presented here, a shortened description of the method development can be found in Pihko (2015). Figure 3 presents the method development process applied in this study.

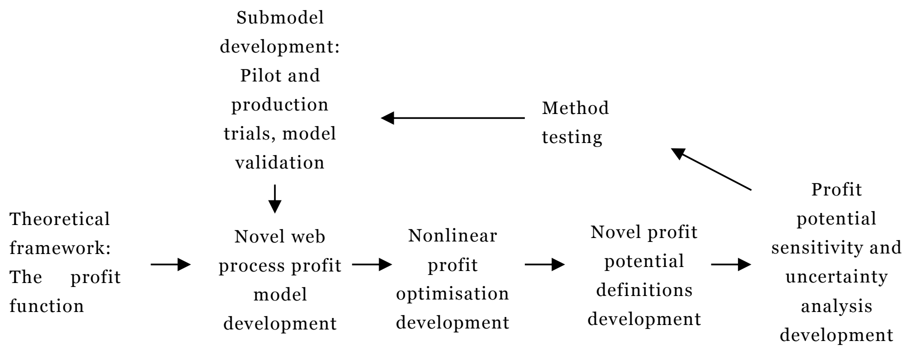


Figure 3. Novel method development process.

In this work, starting from the profit function, a web process line profit model consisting of submodels is developed. To define the profit potential, the profit boundaries are first defined for the current technology and profit optimisation calculation is developed. Then, different optimisation levels of increasing complexity are presented. Depending on the optimisation level, investments and modifications to the technology are included in the calculation. Therefore, further reaching profit boundaries are presented. Finally, process causality, calculation of sensitivity of profit to changes in parameters, and profit optimisation uncertainties calculation procedures are developed. The method is tested and developed further to improve the calculation accuracy.

3.1 Theoretical framework: The profit function and profit maximisation

The profit function (see for example Fuss and McFadden (1978), Färe and Primont (1995), and Coelli (2002)) is the basis for the novel method development. Färe and Primont (1995) present the following definition of the maximum profit function:

$$\Pi\ (\mathbf{p},\mathbf{r}) = \sup_{x,y}\{\mathbf{ry}-\mathbf{px} : (\mathbf{x},\mathbf{y}) \in T\}, \mathbf{p} \in R_{+}^{N}, \mathbf{r} \in R_{+}^{M}, \quad (39)$$

where

$\mathbf{p}$ = input price vector,
$\mathbf{r}$ = output price vector,
$\mathbf{x}$ = input vectors,
$\mathbf{y}$ = output vectors,

and the technology is denoted by T. According to this definition, $\Pi\ (\mathbf{p},\mathbf{r})$ may become $+\infty$.

However, to be able to formulate the profit potential, the limits for the current and the maximum profit should be defined. For this purpose, Coelli et al. (2001) applies earlier presented equations (5) and (6). Applying this definition, the maximum optimised profit, Π^*, is limited by the performance of the best practice companies.

In this work, profit potential calculation should not be limited by the performance level of the best practice companies or the performance of the currently applied technology. Instead of this, the novel method should apply the limitations related to different technologies, driving parameters, market prices and other parameters, which are available from the production and pilot machines, and which are of high interest to web process companies. Therefore a novel profit model and novel profit potential calculation is developed in the next chapters.

3.2 Novel profit model development

In this method, certain web process line is modelled with a process line model consisting of a sequence of submodels. Such simulation models are considered for example in Madetoja and Mäkelä (2006) and in Madetoja et al. (2006). The submodels define the relationships between different parameters influencing the annual profit of a web process. The output of a submodel is passed as input to the next model until the whole chain of models is executed and the profit evaluated. The process line model is directly related to a web process and any changes in the sequence of models imply different process.

The model requires a set of input parameters which initialise the process. These parameters are denoted by $\mathbf{x}$ and they are divided into fixed parameters $\mathbf{x_f}$, which remain unchanged, and variable parameters $\mathbf{x_v}$, which are tuned to maximise the profit. The numbers of fixed and variable input parameters are given by N_f and N_v, while the total number of parameters is denoted by N.

Each parameter $\mathbf{x}$, either fixed or variable, may be either constant over the inspection period or changing annually. The value of a changing parameter at year t is denoted by $\mathbf{x_{f,t}}$ or $\mathbf{x_{v,t}}$, while with constant parameters the subscript t is omitted. The values of the variable inputs have lower and upper bounds given by $\mathbf{l_v}$ and $\mathbf{u_v}$, which limit the optimisation method. Limits for inputs are needed for many reasons. For example the value of the input variable linear nip load should not exceed the maximum allowed load defined for the nip structure. The output of the simulation model is simply the annual profit for year t, and its dependence on the input parameters may be highly nonlinear. The intermediate outputs of submodels are called process quantities.

To define the simulation model for the web process profit the notations of Madetoja and Mäkelä (2006) are applied. The submodels are denoted by A_i, i=1,...,p, and submodel number i takes input parameters $\mathbf{x}$ and outputs of previous submodels $\mathbf{q_j}$, j=1,...,i-1, to produce new process quantity $\mathbf{q_i}$. An example of a submodel is the calculation of the annual saleable production, which uses momentary production, annual production time and total efficiency to obtain the annual production.

An abstract mathematical formulation for the i:th step of the process line model can be given as follows: $A_i(\mathbf{x},\mathbf{q_1},...,\mathbf{q_i})=0$. After the final step all process quantities are available and the annual profit for year t, denoted by Π_t, can be calculated. It is defined as:

$$\Pi_t(\mathbf{x}) = y_t(\mathbf{x})\pi_{mass,t}(\mathbf{x}) - c_t(\mathbf{x}), \tag{40}$$

where

$y_t(\mathbf{x})$ = Web process saleable production (mass unit),
$\pi_{mass,t}(\mathbf{x})$ = Profit per mass unit of product (currency unit / mass unit),
$c_t(\mathbf{x})$ = Cost components (currency unit),

which are all intermediate process quantities $\mathbf{q_i}$.

3.2.1 Submodels development and validation

To be able to calculate the profit, $\Pi_t(\mathbf{x})$, the submodels and input and output parameters, which are presented in more details in Chapter 4.3 and Appendix A, were developed. This was performed in applying the following procedure:

1) Test and data collection planning.
2) Data collection from pilot and production machine trials and tests.
3) Model creation applying real data.
4) Model validation: testing the models with real data, checking the coefficient of determination R^2.
5) Model improvement.

The tests, trials and data collection included pilot scale tests to establish the correct parameters and coefficients to describe the effect of input variables to output variables. The production data collection also included long time period data collection to establish that calculation over a long period (5-10 years) in applying models produces the same values as achieved from real production machines.

Figure 4 presents how the model Web temp after sb, t_{websb}(°C)

$$t_{websb}(°C) = -0,25*(x_{SB}*11/sb_{water})^{\wedge}2 + 4,92*(x_{SB}*11/sb_{water}) + 43,1 \tag{41}$$

where

x_{SB} = Steam box steam (t/h),
sb_{water} = Water at steambox (kg/s),

is formed. The calculation of the submodel sb_{water} is presented in Appendix A.

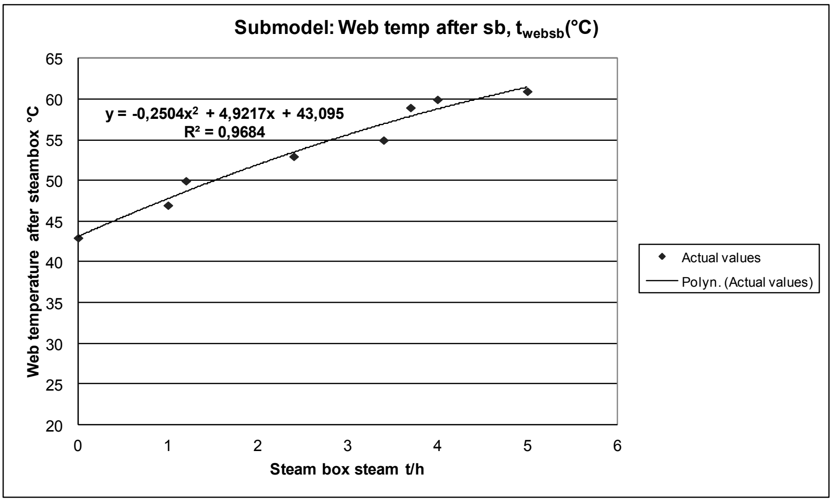


Figure 4. Submodel Web temp after sb, t_{websb}(°C) development and validation.

3.3 Optimisation problem

To calculate the profit over Y years, the same chain of submodels is repeated for each year separately to obtain the values Π_t. Time value of future cash flows is given by the net present value function:

$$\Pi(x) = \sum_{t=1}^{Y} \frac{\Pi_t(x)}{\left(1+r_t\right)^t}, \qquad (42)$$

where r_t is the interest rate at year t. Then, the problem of finding the optimal input parameters to maximise the profit of the current web process technology T can be formulated as the optimisation problem:

$$\Pi^*(T, x_f) = \max_{x_v} \Pi(x_v, x_f) \qquad (43)$$

subject to

$$Le_1 \leq (x_v)_i \leq Ue_i,$$

where $(\mathbf{x_v})_i$ is value of the i:th variable parameter and input value limiting matrices L and U are diagonal with lower and upper bound vectors $\mathbf{l_v}$ and $\mathbf{u_v}$ forming the diagonal entries. The i:th entry of vector $\mathbf{e_i}$ is one while all others are zero. Since some of the variable input parameters $\mathbf{x_v}$ may be constant during the period of Y years, the maximisation of Π can not be performed separately for each year t. An example of $\mathbf{x_v}$ that is constant over inspection period is metal belt length. It can be optimised, but has the same value over the inspection period. Production speed, on the other hand, is marked with $\mathbf{x_{v,t}}$, where t denotes that this variable can be optimised separately each year.

The distance function representation of a production technology is introduced by Shephard (1970). It is summarized and completed, for example, in Färe and Primont (1995) (see also Coelli et al. (2001)). In production theory certain technology is described using the technology set S, which includes all feasible input and output pairs. In this work, the set S corresponds to the process line model. The technology needs to be represented in functional form to be able to measure short term profit. For this purpose, the output distance function is introduced. In this work the model has one output (profit) and there is a direct correspondence between the objective function Π of this optimisation problem and the output distance function D_o of the production theory:

$$D_o(\mathrm{x},\Pi) = \frac{\Pi(x)}{\Pi^*(x_f)}. \tag{44}$$

The value of the distance function is less or equal to one. If the value is one, the variable parameters are technically efficient, while smaller values indicate that there is potential for profit improvement. In this work, the profit values are used instead of the distance function to compare the profit potential in different situations.

In this method the profit function is nonlinear with respect to the variable parameters. This fact separates this work from the production theory with linear profit functions considered, for example, in Fuss et al. (1978) and Coelli et al. (2001). Here, nonlinear optimisation problems for profit maximisation are solved instead of linear programming (LP) problems as in Coelli et al. (2001).

3.4 Optimisation levels and profit potentials

The maximisation of the profit Π is divided on four levels of increasing complexity and different profit potential. The profit in the current situation (Base) is denoted by Π_c and the profit potential is the difference between the maximum profit in the new optimised situation and the current situation:

$$\Pi_{\Delta,k} = \Pi(\mathrm{x}_v^*, \mathrm{x}_\mathrm{f}) - \Pi_c. \tag{45}$$

The subscript k above refers to the optimisation level.

At the lowest level (k=1) only the driving parameters without any modifications of the technology are optimised. This optimisation problem is defined above with the function Π^*, where the variable parameters are controlled within lower and upper bounds. The profit potential is of the form:

$$\Pi_{\Delta,1} = \Pi(\mathrm{x}_v^*, \mathrm{x}_\mathrm{f}) - \Pi_c. \tag{46}$$

The first optimisation level (OptiBase) is illustrated in figure 5 using a profit function with two variable inputs. The function is maximised within the constraints (limits), and depending on the constraints the best possible profit may be reachable or not. The profit function is not necessarily a convex function and the best profit found can be also a local maximum profit.

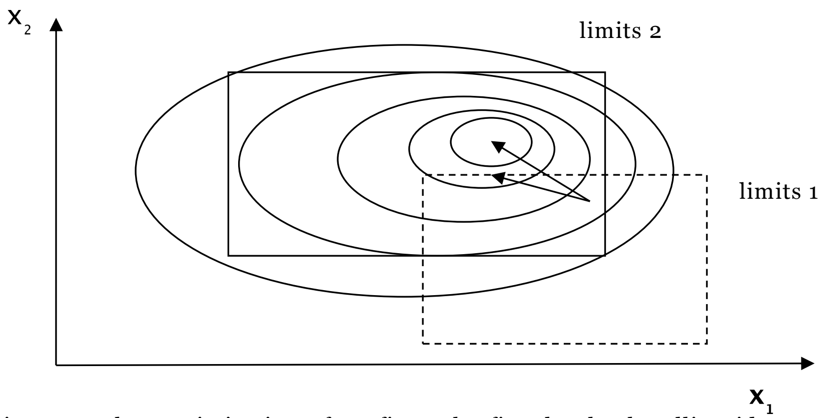


Figure 5. The maximisation of profit at the first level. The ellipsoids are the contour lines of the profit function. Depending on the limits it may be possible to reach the best profit.

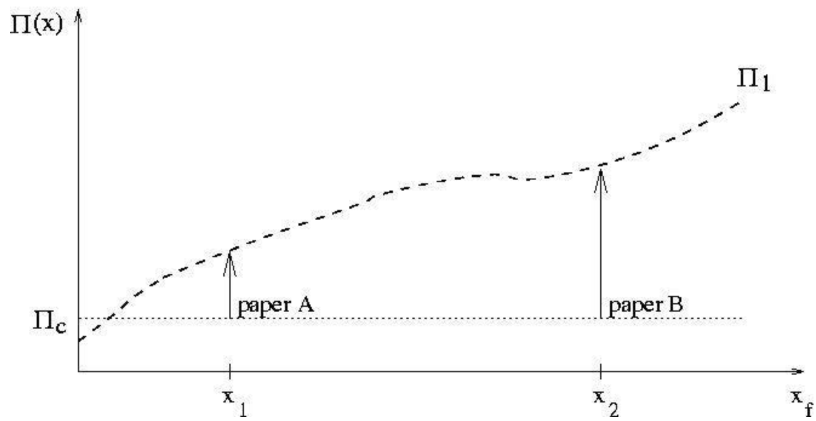


Figure 6. Maximising the profit for two different web grades paper A and paper B. Different web grade corresponds to changes in the fixed parameter values. Here web grade paper B leads to a higher profit.

The profit potential at the lowest level depends on the fixed input parameters x_f although they are not changed in optimisation. The driving parameters of the web process may be optimised for different web grades by making appropriate changes in the values of the fixed parameters and solving several lowest level optimisation problems. A different web grade requires changes at least in the basis weight and sales price. The solutions of the optimisation problems can be compared to decide which web grade is the most profitable. Figure 6 illustrates the profit with respect to a single fixed parameter. Value x_1 corresponds to web grade paper A and value x_2 to paper B, and it can be seen that paper B leads to higher profit.

The second optimisation level (FixedInvest) comprises an investment with fixed cost C. In this theoretical framework, this means a change in the value of some fixed parameter. The investment might require shutting down the current web process production and making some modifications. In order to evaluate the profit potential of the investment, it is needed to take into account the cost of the production shutdown, denoted by S, and the residual value of the investment after the period of Y years, denoted by R. If $r_t>0$, the value of R is discounted. These values depend on some fixed parameter(s) $\mathbf{x_f}$ and the profit in the current situation. Then, the optimisation problem is the same as above except the term R-S-C is added to the profit. The profit potential is of the form:

$$\Pi_{\Delta,2} = \Pi(\mathrm{x}_v^*, \mathrm{x}_f) + R(x_f) - S(\Pi_c, x_f) - C(x_f) - \Pi_c. \quad (47)$$

At the third optimisation level (OptiInvest), also the investment is optimised by changing the status of investment and technology related parameters from fixed to variable $\mathbf{x_f} \rightarrow \mathbf{x_v}$. Then the optimisation problem involves parameters which influence also the technology investment costs, performance, and operating costs, and the profit potential has the form:

$$\Pi_{\Delta,3} = \Pi(\hat{\mathrm{x}}_v^*, \hat{\mathrm{x}}_f) + R(\hat{x}_v) - S(\Pi_c, \hat{x}_v) - C(\hat{x}_v) - \Pi_c. \quad (48)$$

It is emphasised that at the third level the set of variable parameters is larger than at the previous two levels.

In figure 7, the function Π_k (production function) is used to illustrate the profit potential. For simplicity, there is only one fixed parameter related to the investment. The figure shows the production functions corresponding to the current situation (dashed curve, k=1) and after certain investment (solid curve, k=2/3). The vertical arrows correspond to the optimisation of the technology with respect to the variable parameters. The optimisation algorithm starts from the lower end and proceeds to the production frontier shown by the curves. At the first level, production frontier is given by the dashed curve and value of the fixed parameter is x_1. At the second level, production frontier is different because the investment cost, shutdown cost and residual value are taken into account. The value of the fixed parameter is x_2. At the third level the best possible profit is optimised also with respect to the fixed parameter, which reaches the value x^*.

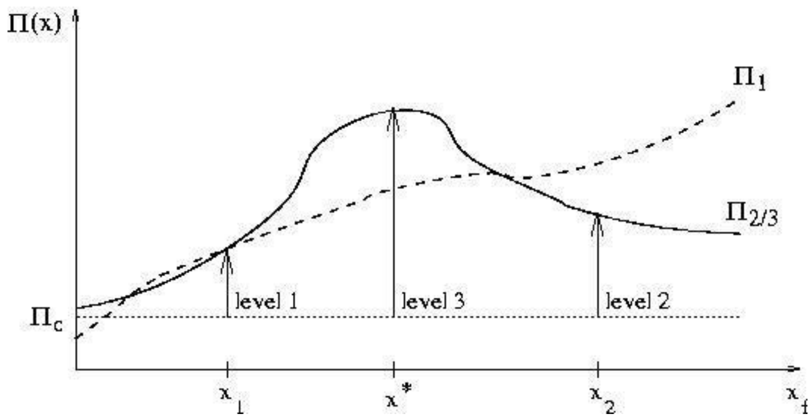


Figure 7. Production functions with the current technology (dashed curve) and the new investment (solid curve). Figure indicates the profit potential at the three different optimisation levels.

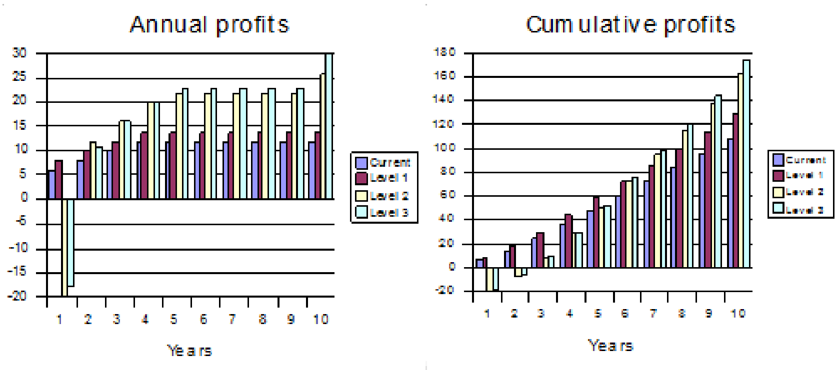


Figure 8. Sample case for the profit of a web process. The chart on the left gives the annual profits of the web process over a period of 10 years and the chart on the right gives the cumulative sum of these profits. The three optimisation levels lead to increasing profit potential.

In figure 8 an example of possible annual profits of a web process over a period of 10 years is presented. The current situation leads to certain profit which can be increased by optimising the driving parameters. A fixed investment causes investment and shutdown costs during the first year but improves the annual profit and residual value such that the profit over the whole period is increased. Optimisation of the investment reduces the investment cost and increases annual profits.

With the optimisation method presented here, it is possible handle the first three complexity levels. However, the fourth level is to introduce more complex changes in the technology which cannot be represented by real valued parameters $\mathbf{x_v}$. The general form of such optimisation problem is:

$$\max_{T \in 0} \Pi^*(T), \qquad (49)$$

where the function is maximised within the set O of chosen technologies. With the current method, different technologies can be compared by trial and error, but automatic optimisation of the technology is a more complicated problem and beyond the scope of this method.

3.5 Numerical method

The net present value function is a linear combination of the nonlinear functions Π_t. The variable input parameters $\mathbf{x_v}$ have lower and upper bounds, and therefore the evaluation of the maximum profit F(T) is a constrained nonlinear optimisation problem. A classical method for such problems is SQP (Sequential Quadratic Programming), which is an efficient gradient-based method. The optimisation in this method is made by SQP with a simple line search algorithm (for details, see Haataja (2004) or Nocedal and Wright (2000)).

The basic idea of SQP is to form a sequence of quadratic problems the solutions of which converge to the solution of the original problem. During each iteration step, a quadratic optimisation problem is solved to find an optimisation direction **p**. Then the line search algorithm is used to determine suitable step size r such that

$$\Pi(x + rp) > \Pi(x). \qquad (50)$$

The iterations are terminated when the algorithm has converged.

During iteration, SQP method requires computation of the gradient of Π with respect to the variable parameters. The computation of the partial derivatives of a function like Π, which is based on a sequence of models is considered in Madetoja et al. (2006). With automatic differentiation techniques the following derivatives

$$\frac{d\,\Pi(x)}{dx_v} \qquad (51)$$

are obtained automatically as the simulation model[1] is evaluated and they describe the sensitivity of the profit with respect to the variable parameters. The large value indicates that a change in the corresponding variable leads to large changes in the profit. SQP method attempts to find such values of $\mathbf{x_v}$ that the gradient of Π becomes zero (profit cannot be improved by changing $\mathbf{x_v}$). It is possible that such a condition is satisfied also at some other location than the global maximum (local maximum). Then, this method fails to find the best possible situation. The possibility of meeting local maximum can be reduced by repeating the optimisation method from different starting values for $\mathbf{x_v}$.

Each parameter is restricted to the interval $[\mathbf{l_v},\mathbf{u_v}]$ and to make the gradient components comparable, the variables are scaled to the range [0,1]. This implies that the sensitivity value given by the simulation model needs to be multiplied by the difference of the upper and lower bounds: $(\mathbf{u_v}-\mathbf{l_v})$. The scaled sensitivity values are then used to compare the importance of different variables in the maximisation of the profit.

Strictly, this method requires all submodels A_i to be smooth functions, which is not always the case. There may be some isolated points where the function is nonsmooth. There are methods for nonsmooth optimisation which use subgradient information (see Madetoja and Mäkelä (2006)), but they are not utilised here.

3.6 Simulation analysis

3.6.1 Process causality

To understand the causality between the model control variables $\mathbf{x_v}$ and output parameter Π, simulations can be calculated in series to produce a dataset. To study the effect of one control variable the other variables can be kept constant and change the value of the chosen variable with fixed steps. The visualisation of this dataset provides understanding about the behavior of the simulation model. The range of the variable variation and

[1] Appendix A presents the applied model and the parameters.

the step size determine how detailed information about the causality is produced.

For multidimensional analysis where there exist many varying input variables it is needed to run a dataset of input variables. Such a dataset gives possibility to analyse the interactions between the input variables.

In addition, it is possible to estimate the worst and best case scenario together with the expected one (figure 9). Giving the variables values that represent the worst and best possible situation it is possible to screen the range of the result variation. Variation of the variable values should be chosen according to practical experience and knowledge. For example, price development data for different pulp, board and paper grades can be applied to forecast best and worst scenario price levels for these grades in the future.

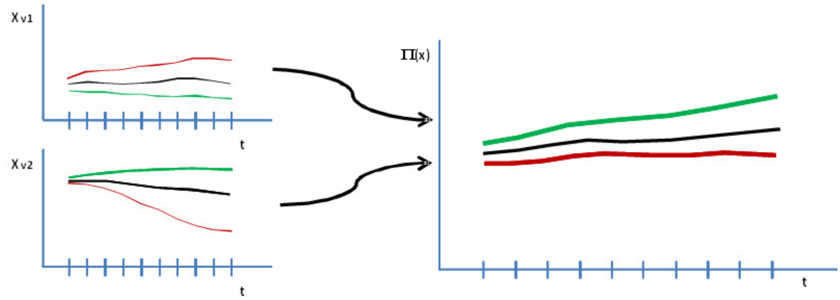


Figure 9. An illustration of scenario testing using simulation. The worst case scenario is presented by the red line, expected scenario by the black, and the best scenario by the green line.

Currently, the variable scenarios or datasets can be simulated applying one simulation at a time. In future, user interface and simulation model can be further developed to run advanced simulations in a simulation series.

3.6.2 Sensitivity analysis

As mentioned earlier (see equation (51)) the derivatives of the parameter Π can be applied to a sensitivity analysis. The derivative presents the changing speed of the parameter Π with respect to the change of the control variable $\mathbf{x}_v$. The unit of the derivative is [response variable unit / control variable unit]. To compare the sensitivity of the response variable to the changes of different control variables, the derivative values need to be scaled to comparable control changes.

With this model entity there are scalar size control variables with one value effecting each year of the calculation period. The annually changing control variable is presented as a vector. The size of the derivative is same as the size of the control variable. The derivative is scalar for a scalar control variable and vector for a vector type control. The scalar parameter has an effect on each year over the inspection period, but each vector element of the vector type parameter effects on only one year profit. To be able to compare the output sensitivity between different types of control variables the absolute values of the derivative vector elements are summed up. These calculated values give the potential of the vector variable to effect output variable that is comparable with the scalar value.

It must be noted, however, that although the gradient of Π is easy to derive, it gives only local information (see figure 10) about the sensitivity with respect to variable parameters and may therefore lead to false conclusions.

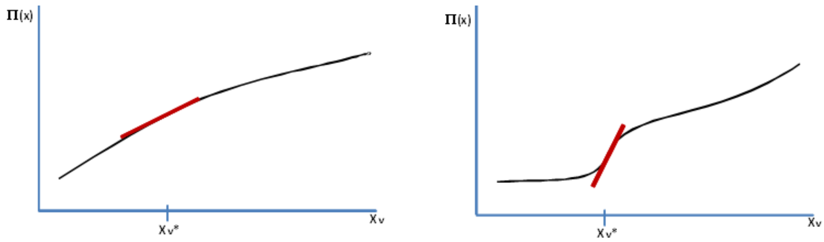


Figure 10. An example of derivative based sensitivity information in different function. In the left graph the gradient information at the point **x_v*** represent the output sensitivity in large window. In the right graph the function is highly nonlinear and the gradient information is valid only in a narrow window.

3.6.3 Uncertainty analysis

For uncertainty analysis, this novel method applies Markov chain Monte Carlo (MCMC) type of simulation. Monte Carlo simulations can be used to assess the uncertainty related to certain input parameters of the model (see Savvides (1994)). Monte Carlo methods are computational algorithms that rely on repeated random sampling to compute their results. In uncertainty analysis the random samples of the chosen variables are simulated from the multidimensional probability distribution. It is to be noted that the uncertain variables can be both process control variables and model parameters. The model entity is evaluated with the simulated input values. The model outcomes are a sample of the output variable distribution.

The required uncertainty information can be analysed from the simulated output samples. The most used characteristic values are the expected values, standard deviations, coefficient of variation, correlation, and confidence intervals. There are also methods to approximate the actual output distribution such as histograms and Kernel density estimation (Hastie et al 2001).

For accurate uncertainty analysis the sample size related to input parameters should be large. Typically at least hundreds to thousands of samples per parameter is needed in order to have the error bound on the estimate small enough. The more uncertainty sources are considered the more samples are needed. Large sample size means many simulations. These can require considerable amount of computation time.

Accurate confidence information of the input variables is essential for reliable uncertainty estimation. It is often a difficult task to define accurately the probability distribution of the variables as well as, the dependencies between the variables.

Calculation applied to the sample from the joint probability distribution produces a sample of the output probability distribution. Figure 11, the right hand side graph describes this distribution, which is the approximated probability distribution of the profit potential output variable. Here, all the other input variables have deterministic i.e. fixed values, except the two stochastic inputs.

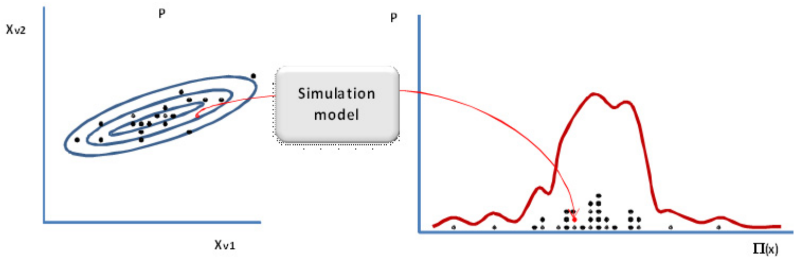


Figure 11. The basic idea of Monte Carlo method applied in uncertainty analysis.

This novel method applies MCMC simulation for uncertainty estimation. For the simplicity of the definition of input and model parameter uncertainties, the parameter uncertainties are considered as independent. To understand correlations between the parameters, simulation series can be run (see 3.6.1 Process causality). The used procedure for the sample simulation is described in Johnson (1987).

This novel method applies two distributions for the parameter uncertainty: normal and uniform distributions. Normal distribution is useful for many parameters since for example mass-produced items (parameters) usually follow a normal distribution. Uniform distribution where all the values within the allowed range have the same probability density can be applied if the parameter is poorly known. For both distributions the expected value of the parameter is defined in the profit potential calculations. The deviation of the uncertain parameter is defined according to the distribution. For a uniform distribution the deviation parameter define the maximum range of the parameter value variation from the expected value of the parameter. For a normal distribution the deviation value is a standard deviation σ of the parameter.

Within a normally distributed vector sized parameter, the elements of the vector can be correlated. The correlation between the neighboring vector elements is defined by a correlation coefficient ρ. In profit potential calculations this means correlation between contiguous years. The covariance matrix for the uncertain vector parameter (in three years calculation period) would be in the form:

$$\begin{bmatrix} \sigma^2 & \rho\sigma^2 & 0 \\ \rho\sigma^2 & \sigma^2 & \rho\sigma^2 \\ 0 & \rho\sigma^2 & \sigma^2 \end{bmatrix},$$

where σ^2 is the combined variance of the vector elements, and ρ is a correlation coefficient, which can have values between [-1,1]. A negative correlation coefficient means that when the value of one vector element is increasing, the value of the neighboring vector element is decreasing.

Vector parameters, where there exists correlation between the vector elements, are simulated as follows:

- A sample, X, is formed from vector's standard normal distribution, (N(0,I)).
- Factor c is solved applying Cholesky decomposition of parameter's covariance matrix, ∑, so that ccT=∑.
- A correlated sample, Y, from distribution N(μ,∑) is formed applying the equation Y= μ+cX. μ is an average value vector.

As a result of the Monte Carlo simulation the percentiles of the output parameters are given between 2.5% to 97.5% in 2.5% steps. These percentiles are used for cumulative probability function estimation for the output parameters (see figure 12).

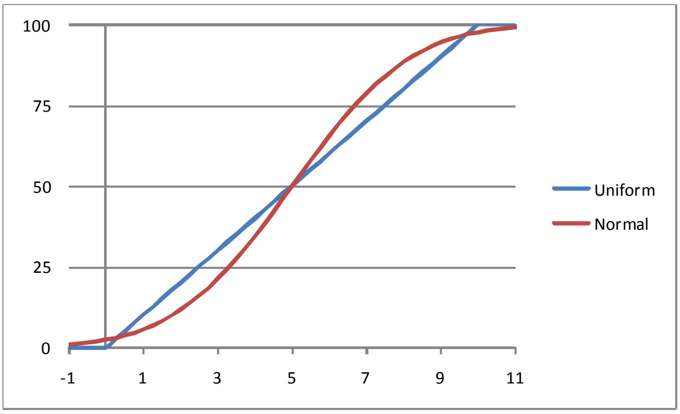


Figure 12. Examples of the cumulative probability functions for uniform and normal distributions. The value on the x-axis is the parameter value. The y-axis value gives the probability in percents for the parameters to have a value less than the given x-value.

The uncertainty analysis could be further improved by:

- A random walk type uncertainty definition for the vector type parameters to define an increasing uncertainty over the defined time period.
- Considering the correlation between different parameters.
- Estimating the probability function for the output parameters along with the applied cumulative probability.

3.7 Method testing and validation

An example of method testing is presented in the next Chapter 4, where the method is applied to two different types of web production lines. In addition to this, during the development of the method, the method was tested by different calculations applying data from production machine investments.

There were several rebuilds i.e. changes of components in production lines calculated, and there were new production line investments calculated where profit cumulation over several years was followed. During the development of the method there were also new process components developed and tested and models describing these technologies (for example metal belt technologies) were developed, tested, and validated.

Validation of the method, models, and calculation was based on comparison of the calculation results (output parameters) with the results and data collected from the production and pilot machines. It is to be noted that applying the same input values, the output values concerning profit were the same as achieved from the production machines. Also one key figure, payback period, was calculated in several investment cases and it had the same value applying the novel method calculation compared to calculations carried out by the mill personnel applying the data and calculation methods applied on the production machines. The payback periods calculated during the research varied from one month to 6 years depending on the type of the investment.

4 APPLICATION OF THE NOVEL METHOD

This chapter presents application of the novel method to web process profit optimisation, to web process development, and to other products and industries.

At first, the current technology web processes (SC and Board) are presented. The main limitations related to the current technology are discussed and new technology is presented. New technology can overcome many of the limitations related to the current technology and these features are presented.

The main parameters connecting the technology and the novel profit model are presented. At the first optimisation level (Base) this novel method with certain variable input parameters is applied to determine the maximum profit achievable with the current technology. At the second optimisation level (FixedInvest) investment in new technology is included. At the third level (OptiInvest) the new technology is optimised to find out the optimal parameter values, which produce the maximum profit achievable over a time period. Sensitivity and uncertainty related to calculations are presented.

Finally, this chapter brings out a general perspective how to apply this novel method to continuous web process development. In addition, this novel method can be applied to other products and industries. At the end of this chapter this novel method is developed further for other types of products. There market factors are included into the calculation model.

4.1 SC web process technology

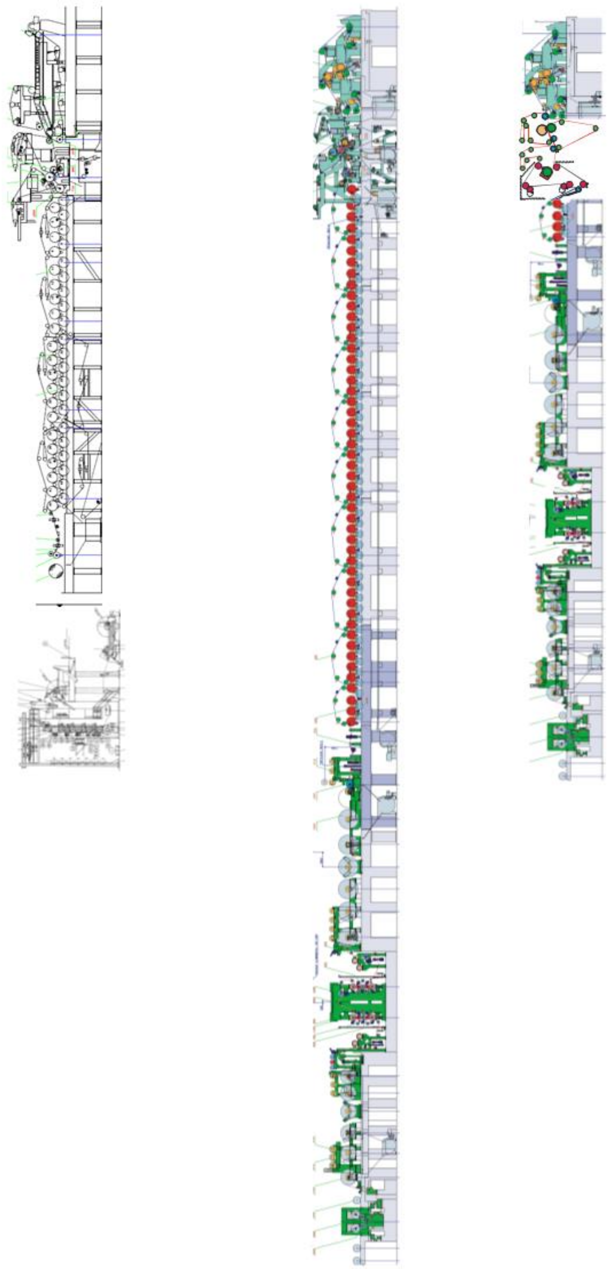
A Super Calendered (SC) web process line produces smooth and dense paper. Here the current old, the current prior art, and the new technology processes are presented (see figure 13).

The current old technology applies a horizontal forming section, 3 roll press nips with an open draw after the press section, a relatively long dryer section, and 2 x 6…8 calender nips. The production is limited by the web breaks at the press and dryer sections and by the web quality at high production speed.

The current prior art technology applies a vertical forming section, a 4 nip press section with a shoe nip at the 3^{rd} nip position and an open draw after the press section, a long dryer section and 2 x 8…12 calender nips. The prior art technology can produce better quality and higher amount of production compared to the old technology. The production is limited by the web breaks and by the web quality at high production speed.

The new technology applies a novel extended wet pressing nip design combined with a novel steam heated metal belt pressing, drying and calendering technology. The new technology details are described in Pihko and Savela (2009) and Pihko and Laapotti (2009). The new technology arrangement increases web dryness and smoothness in a small space and therefore there is only a short cylinder dryer section and a few end calendering nips needed to produce high quality SC web at a high speed level. This decreases investment and operating costs. Due to high dryness and strength of the web combined with the closed web transfer, it is possible to avoid web breaks and to increase filler amount and thus decrease raw material costs.

The current old technology, Base, OptiBase | The current prior art technology, FixedInvest | The new technology, OptiInvest



The main models:

- Dryness after press
- Dryness after press + pressmb + imp
- Pressmb investment
- Dryer section investment
- Dryer section machine hall investment
- Calender investment
- Pressmb steam
- Dryer section steam
- Calender energy consumption
- Annual break time
- Annual shutdowns
- Annual production
- Maintenance and wearing part expenses

Figure 13. SC web process technology.

4.2 Board web process technology

A board web process line produces a high basis weight layered and coated product. Important properties for this product are high strength, bulk and smoothness.

The current prior art technology applies layered forming, 2 shoe press nips + a smoothing press, a very long dryer section, sizing, coating, calendering and intermediate drying processes. The production line is very long and expensive. If dryness after press section is increased by increasing the nip loads, less bulk and stiffness is achieved. Then, to reach the targeted product stiffness a high amount of expensive raw material is needed.

The new technology applies a novel extended metal belt pre-pressing nip combined with a novel steam heated metal belt pressing, drying, and calendering technology. The new technology details are described in Pihko and Pakarinen (2010), Pihko and Savela (2009) and Pihko and Turunen (2009). The new technology increases web dryness and smoothness very efficiently with a low peak pressure in the nips. As a result a high quality (smoothness and stiffness) web can be produced at a high production speed. Compared to the prior art technology there are less process parts and investment and operating costs needed. Additionally, due to an improved stiffness the production can apply less and/or lower cost raw materials compared to the prior art to reach the quality targets.

The board production lines and the main models are presented in figure 14. Here, also the model Basis weight required to produce product is applied. This model takes account the effect of the last press nip load and possible application of the metal belt technology on the required basis weight to produce the product. The calculated required basis weight (bw) is applied to calculate for example the achieved dryness and the dryer section length. Therefore the applied basis weight has an effect on the investment, operating and maintenance costs. The applied models, parameters, and model connections are described in more details in the next Chapter 4.3 and in Appendix A.

The current prior art technology, Base, OptiBase

The new technology, FixedInvest, OptiInvest

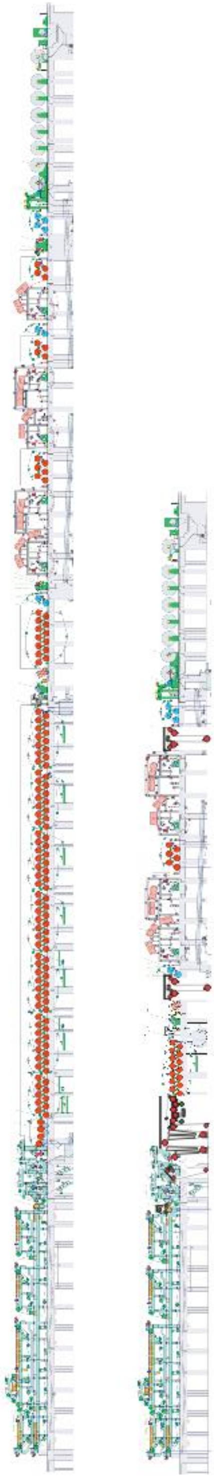


Figure 14. Board web process technology.

The main models:

- Basis weight required to produce product
- Dryness after press(bw)
- Dryness after press + pressmb + imp (bw)
- Pressmb investment
- Dryer section investment (bw)
- Dryer section machine hall investment (bw)
- Calender investment
- Pressmb steam
- Dryer section steam (bw)
- Calender energy consumption
- Annual break time
- Annual shutdowns
- Annual production (bw)
- Maintenance and wearing part expenses (bw)

4.3 Web process parameters and models

Application of this novel method to web process applies web production process input parameters, intermediate output models and parameters and profit models and parameters. From profit models profit potentials at different optimisation levels are calculated. The model system has 49 unit models, 62 input parameters and 74 output parameters per optimisation level. Figure 15 presents the main parameter and model groups. Figure 16 presents the model connections. The exact parameters and models are presented in Appendix A.

It is to be noted here that the connections between the technology parameters, press nip load, dryness, speed, breaks, investment costs, quality related raw material need for required stiffness and maintenance and energy costs are included in the model system. Speed related effects on investment and maintenance costs, energy consumption, dryness and breaks are also included. In addition, the connection between the quality and speed can be applied during simulations.

Input parameter groups

General
Efficiency
Prices
Investment
Process

Output parameter groups

General
Process
Energy press, dryer, cal
Investment
Efficiency
Production
Energy, total
Energy prices per mass unit of product
Profits and expenses

Profit potentials on optimisation levels

$$\Pi_{\Delta,1} = \Pi(x_v^*, x_f) - \Pi_c$$

$$\Pi_{\Delta,2} = \Pi(x_v^*, x_f) + \frac{R(x_f)}{(1 + r_t/100)^Y} - S(\Pi_c, x_f) - C(x_f) - \Pi_c$$

$$\Pi_{\Delta,3} = \Pi(\hat{x}_v^*, \hat{x}_f) + \frac{R(\hat{x}_v, \hat{x}_f)}{(1 + r_t/100)^Y} - S(\Pi_c, \hat{x}_v, \hat{x}_f) - C(\hat{x}_v, \hat{x}_f) - \Pi_c$$

Figure 15. The main parameter and model groups.

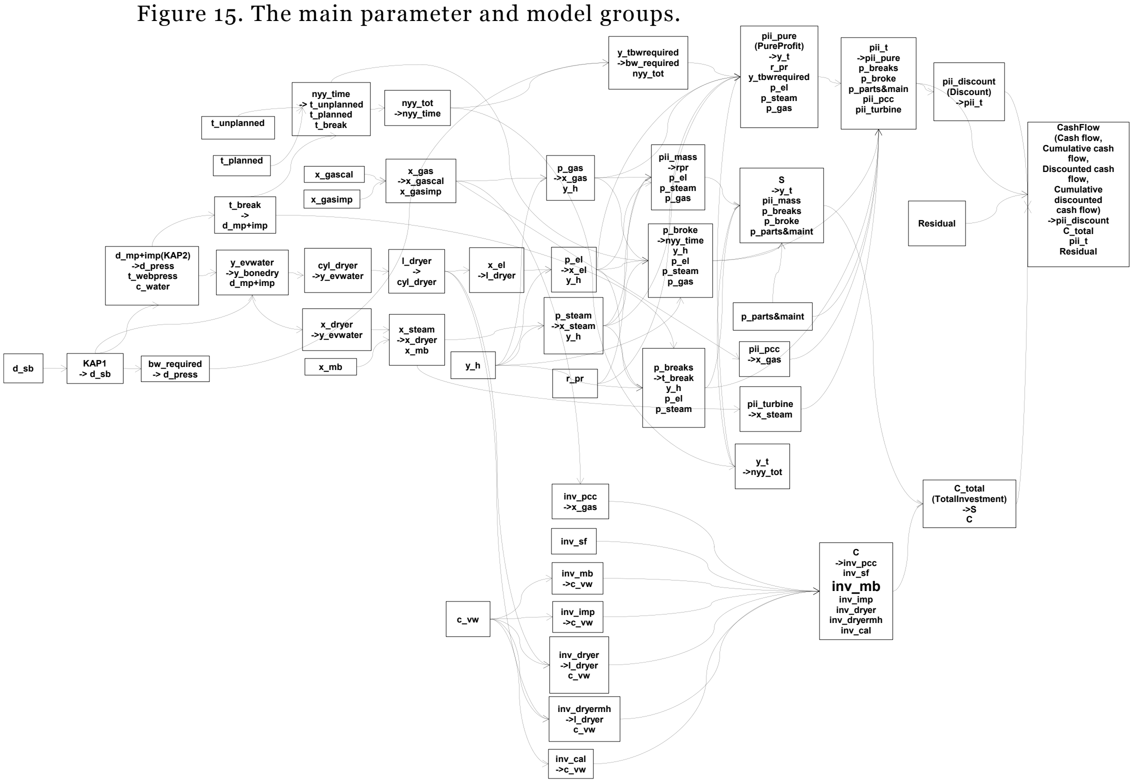


Figure 16. The models and connections.

4.4 SC web process profit potentials $\Pi_{\Delta,1...3}$

At the first optimisation level the current old technology with the current driving parameter setting Base produces the profit Π_c. When the current old technology is optimised with respect to driving input parameter speed v the result is the optimised current old technology OptiBase. The profit potential at the first optimisation level is $\Pi_{\Delta,1}$. All the applied models are presented in Appendix A, the applied input parameters in Appendix B and the applied technology in Chapter 4.1.

The first optimisation level OptiBase and the profit potential $\Pi_{\Delta,1}$ are calculated as:

$$\Pi(v^*, x_f) = \max_v \Pi(v, x_f) \tag{52}$$

subject to

$$1200 \text{ m/min} \leq v \leq 2000 \text{ m/min}$$

$$\Pi_{\Delta,1} = \Pi(v^*, \mathrm{x_f}) - \Pi_c \tag{53}$$

The second optimisation level FixedInvest refers to a fixed investment where the current old technology Base is replaced with the current prior art technology FixedInvest. The prior art technology is optimised with respect to the driving parameter speed, 1200 m/min≤v≤2000 m/min, according to equation (51). The profit potential $\Pi_{\Delta,2}$ is:

$$\Pi_{\Delta,2} = \Pi(v^*, \mathrm{x_f}) + R(x_f) - S(\Pi_c, x_f) - C(x_f) - \Pi_c \tag{54}$$

The third optimisation level OptiInvest refers to the new technology. Optimisation of the new technology is carried out with respect to the driving parameter speed v and investment and process related parameter metal belt effective length l_{mbeff}. The parameter l_{mbeff} is changed from fixed to variable parameter. The parameter l_{mbeff} has an effect on dryness after metal belt, cylinder dryer section and machine hall length, investment costs, web break time, and operating energy and maintenance costs. The profit potential $\Pi_{\Delta,3}$ is calculated as:

$$\Pi(v^*, l^*_{mbeff}, \hat{x}_f) = \max_{v, l_{mbeff}} \Pi(v, l_{mbeff}, \hat{x}_f) + \frac{R(v, l_{mbeff}, \hat{x}_f)}{(1 + r_t/100)^Y} - S(\Pi_c, v, l_{mbeff}, \hat{x}_f) - C(v, l_{mbeff}, \hat{x}_f) \tag{55}$$

subject to

$$1200 \text{ m/min} \leq v \leq 2000 \text{ m/min}$$
$$0 \text{ m} \leq l_{mbeff} \leq 30 \text{m}$$

$$\Pi_{\Delta,3} = \Pi(v^*, l^*_{mbeff}, \hat{x}_f) + \frac{R(v^*, l^*_{mbeff}, \hat{x}_f)}{(1 + r_t/100)^Y} - S(\Pi_c, v^*, l^*_{mbeff}, \hat{x}_f) - C(v^*, l^*_{mbeff}, \hat{x}_f) - \Pi_c \tag{56}$$

The result of the calculation as cumulative cash flows over the period of 10 years is presented in figure 17.

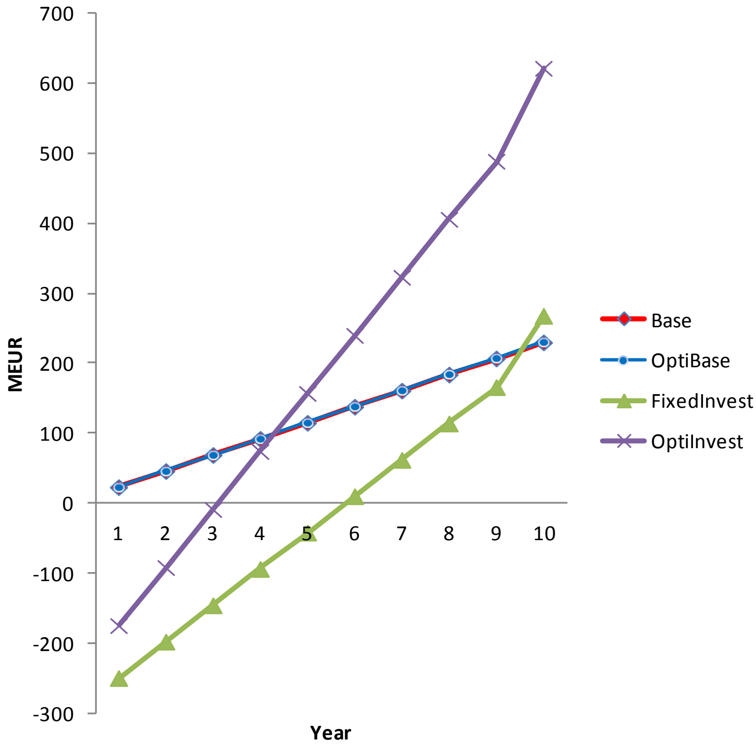


Figure 17. SC web process, cumulative cash flows.

The calculation produces the following profit potentials:

$\Pi_{\Delta,1}$ = 0,8 MEUR

$\Pi_{\Delta,2}$ = 50,2 MEUR

$\Pi_{\Delta,3}$ = 397,0 MEUR

4.5 Board web process profit potentials $\Pi_{\Delta,1...3}$

At the first optimisation level OptiBase the current prior art technology is optimised with respect to the driving parameter last press nip load $f_{lastnip}$:

$$\Pi(f^{*}_{lastnip}, x_f) = \max_{f_{lastnip}} \Pi(f_{lastnip}, x_f) \tag{57}$$

subject to

$$800 \text{ kN/m} \le f_{lastnip} \le 1500 \text{ kN/m}$$

$$\Pi_{\Delta,1} = \Pi(f^{*}_{lastnip}, x_f) - \Pi_c \tag{58}$$

Here the last press nip load has an effect on dryness, raw material (basis weight) required for stiffness, dryer section and machine hall length, and investment and operation costs. The models are presented in Appendix A, and the initial input values in Appendix C.

At the second optimisation level FixedInvest the new technology is calculated applying the driving parameter last press nip load $f_{lastnip}$ optimisation according to equation (57).

$$\Pi_{\Delta,2} = \Pi(f^{*}_{lastnip}, x_f) + R(x_f) - S(\Pi_c, x_f) - C(x_f) - \Pi_c \tag{59}$$

At the third OptiInvest optimisation level the new technology is optimised with respect to the production speed v, metal belt length l_{mbeff}, and last press nip load $f_{lastnip}$.

$$\Pi(v^{*}, l^{*}_{mbeff}, f^{*}_{lastnip}, \hat{x}_f) = \max_{v, l_{mbeff}} \Pi(v, l_{mbeff}, f_{lastnip}, \hat{x}_f) + \frac{R(v, l_{mbeff}, f_{lastnip}, \hat{x}_f)}{(1 + r_t/100)^Y} - S(\Pi_c, v, l_{mbeff}, f_{lastnip}, \hat{x}_f) - C(v, l_{mbeff}, f_{lastnip}, \hat{x}_f) \tag{60}$$

subject to

$$500 \text{ m/min} \le v \le 1000 \text{ m/min}$$
$$0 \text{ m} \le l_{mbeff} \le 70 \text{m}$$
$$800 \text{ kN/m} \le f_{lastnip} \le 1500 \text{ kN/m}$$

OptiInvest $$\Pi_{\Delta,3} = \Pi(v^{*}, l^{*}_{mbeff}, f^{*}_{lastnip}, \hat{x}_f) + \frac{R(v^{*}, l^{*}_{mbeff}, f^{*}_{lastnip}, \hat{x}_f)}{(1 + r_t/100)^Y} - S(\Pi_c, v^{*}, l^{*}_{mbeff}, f^{*}_{lastnip}, \hat{x}_f) - C(v^{*}, l^{*}_{mbeff}, f^{*}_{lastnip}, \hat{x}_f) - \Pi_c \tag{61}$$

The result of the calculation over the period of 10 years is presented in figure 18.

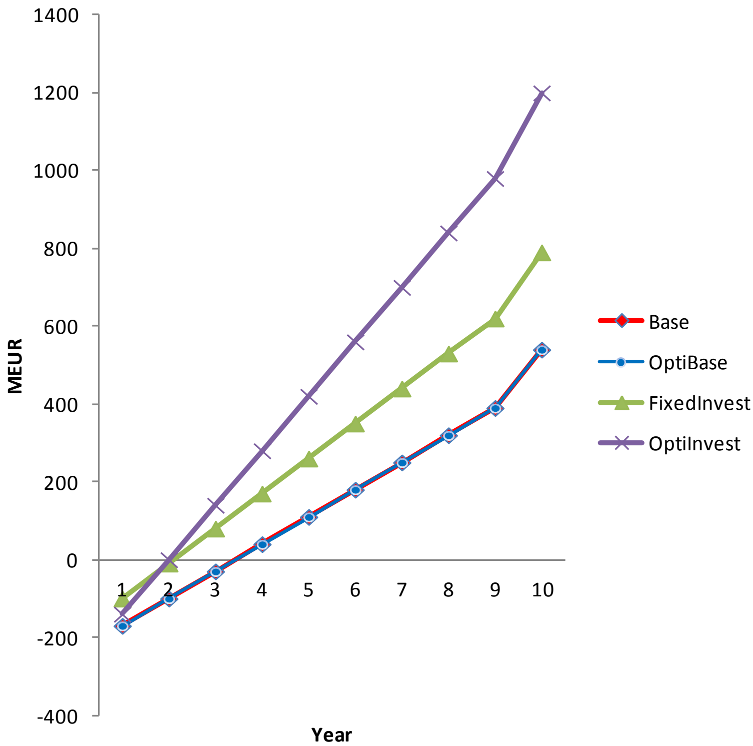


Figure 18. Board web process, cumulative cash flows.

The calculation produces the following profit potentials:

$\Pi_{\Delta,1}$ = 0,0 MEUR

$\Pi_{\Delta,2}$ = 267,5 MEUR

$\Pi_{\Delta,3}$ = 685,6 MEUR

4.6 Sensitivity analysis for web process profit potentials

The sensitivity of the profit potentials with respect to the variable parameters is calculated here for SC and Board web processes at the OptiInvest optimisation level.

- + indicates that profit potential increases when parameter increases.
- - indicates that profit potential decreases when parameter increases.
- +- indicates that profit potential can increase or decrease when parameter increases.
- Grad. is the value of the gradient with respect to parameter at the calculation point.

The result of the calculation over the inspection period of 10 years for the parameters that have an increasing impact on profit potential is presented in figures 19 and 20. It is to be noted that the result (see Grad. values) is local sensitivity. PCC production investment and application of back-pressure turbine indicate high values due to the nature of these models: These models are on/off type of models at this calculation point. Despite the fact, applying PCC production, a back-pressure turbine and an increment in web width would lead to a significant increase in profit potential. Therefore, application of sensitivity analysis of the novel method brings out the order of importance related to the parameters. Development of technology behind these parameters (technological steps) can lead to further profit improvements.

Sensitivity | Uncertainty

OptiInvest

Calc

Param. name	+ -	Grad.	M€	Sc...	Unit
Steam box steam	+ -	1,032	M€	1	t/h
Felt steamer steam	+ -	0,996	M€	1	t/h
Back-pressure turbine	+	3 348	M€	1	
PCC production investment	+	684,175	M€	1	
Web width	+	108,392	M€	1	m
Product basis weight	+	20,67	M€	1	g/m2
A quality product market price at speed below vq	+	4,548	M€	1	EUR/t
Ref dryness before steam box	+	2,555	M€	1	%
Product moisture after dryer section	+	2,421	M€	1	%
Ref dryness after press concept at design nip loads witho...	+	1,843	M€	1	%
Investment residual value after inspection period	+	1	M€	1	MEUR
Production speed	+	0,387	M€	1	m/min
Tappi drying rate	+	0,246	M€	1	kgH20/m^2h
Maximum available annual operating time	+	0,12	M€	1	h
Ref production speed	+	0,119	M€	1	m/min
Impingement effective drying length	+	0,055	M€	1	m
Last press nip load	+	0,004	M€	1	kN/m

Figure 19. Sensitivity analysis for SC profit potential $\Pi_{\Delta,3}$.

Sensitivity | Uncertainty

OptiInvest

Calc

Param. name	...	Grad.	M€	S...	Unit
Felt steamer steam	+ -	0,928	M€	1	t/h
Steam box steam	+ -	0,806	M€	1	t/h
Production speed	+ -	0,512	M€	1	m/min
Back-pressure turbine	+	17 054,751	M€	1	
PCC production investment	+	276,546	M€	1	
Web width	+	205,92	M€	1	m
Ref dryness before steam box	+	16,346	M€	1	%
A quality product market price at speed below vq	+	9,54	M€	1	EUR/t
Product moisture after dryer section	+	8,048	M€	1	%
Product basis weight	+	4,804	M€	1	g/m2
Ref dryness after press concept at design nip loads without sb, fs, pressmb	+	3,868	M€	1	%
Ref production speed	+	2,489	M€	1	m/min
Tappi drying rate	+	2,343	M€	1	kgH20/m^2h
Investment residual value after inspection period	+	1	M€	1	MEUR
Pressmb drying effective length	+	0,861	M€	1	m

Figure 20. Sensitivity analysis for Board profit potentials $\Pi_{\Delta,3}$.

4.7 Uncertainty analysis for Board web process profit potentials

The uncertainty related to profit potential with respect to certain input variable and model parameters is calculated here for Board web process profit potentials. The following parameters are applied to uncertainty analysis in this application example:

- A quality product market price at speed below v_q, r_{pra}(EUR/t), $\mathbf{x_{f,t}}$.
- Pulp price, p_{pulp}(EUR/t), $\mathbf{x_{f,t}}$.
- Pressmb coefficient c0, $\mathbf{x_f}$. c0 is pressmb investment costs (MEUR)/pressmb effective length (m) at certain scale.
- Pressmb coefficient c1, $\mathbf{x_f}$. c1 is pressmb investment initial costs at certain scale (MEUR).

The main input values related to uncertainty calculation and the results of the calculation over the period of 10 years are presented in figure 21. The result presents that even when there are uncertainties related to many input parameters at the same time, the expected new optimised metal belt technology profit potential will have a high value ($\Pi_{\Delta,3}$ is 626-756 MEUR). On the other hand, the profit potential applying the current technology can have a negative value ($\Pi_{\Delta,1}$ is -20 MEUR) and in worst case changes in prices can lead to losses compared to the current situation. Therefore, application of the method to uncertainty analysis produces important information about the risks and possibilities related to the novel technology and important parameters. Based on this information, the critical parameters related to the new technology and production profitability can be monitored and necessary actions can be carried out to minimise these risks.

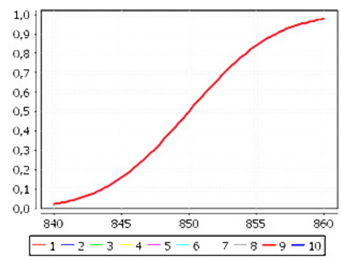
Input parameters and deviation and correlation values are presented on the upper graphs. The lower graphs present the output values. The graph “Outputs Vis” presents the effect of correlation and cumulative uncertainty: When price input values have high (or low) values during the first year of calculation, it is probable that the values during the next year will stay high (or low), and therefore, the deviation in cumulative cash flow during the last year will be quite large.

The graph “Profit Potential Vis” presents that there is new metal belt technology related input parameter uncertainty in OptiInvest that is not applied to OptiBase and FixedInvest calculations. Due to this additional uncertainty, OptiInvest profit potential $\Pi_{\Delta,3}$ has greater deviation compared to OptiBase and FixedInvest profit potentials $\Pi_{\Delta,1}$ and $\Pi_{\Delta,2}$.

Inputs

	Parameter	Unit	Distribution	Deviation	Correlation
☐	Chemical price	EUR/t	<No dist>	0	□
☐	Packaging material	EUR/t	<No dist>	0	□
✔	**A quality product market price at spee...**	**EUR/t**	**N(0.85,0)**	**10**	**0,5**
☐	B quality product market price at spee...	EUR/t	<No dist>	0	□
☐	Other operating material	EUR/t	<No dist>	0	□
☐	Filler, coat, size price	EUR/t	<No dist>	0	□
✔	Pulp price	EUR/t	N(0.5,0)	10	0,5
☐	Product transportation price	EUR/t	<No dist>	0	□
☐	Water price fresh and effluent	EUR/t	<No dist>	0	□
☐	Product comission fee price	EUR/t	<No dist>	0	□
☐	Quality change speed	m/min	<No dist>	0	□

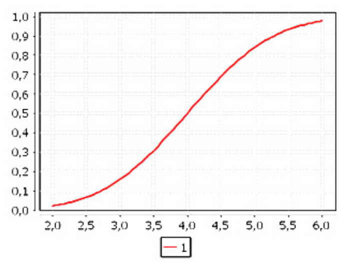
Vis



Inputs

	Parameter	Unit	Distribution	Deviation	Correlation
☐	t_unplanned.c1	-	<No dist>	0	□
✔	Pressmb.c0	-	N(0.04,0)	0,02	0
☐	t_planned.c0		<No dist>	0	□
☐	Prepressmb.c0	-	<No dist>	0	□
☐	t_unplanned.c0	-	<No dist>	0	□
✔	**Pressmb.c1**	**-**	**N(4,1)**	**2**	**0**
☐	Prepressmb.c1	-	<No dist>	0	□
☐	t_planned.c1		<No dist>	0	□

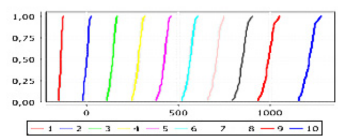
Vis



Outputs

Parameter	Unit	Mean	Median	L95	U95
Cumulative discounted cash flow	MEUR	421,731	424,672	378,409	461,353
Cash flow	MEUR/a	141,555	141,523	131,442	154,054
Discounted cash flow	MEUR/a	141,555	141,523	131,442	154,054
Discounted annual profit	MEUR/a	141,555	141,523	131,442	154,054
Cumulative cash flow	**MEUR**	**421,731**	**424,672**	**378,409**	**461,353**
Cumulative discounted annual profit	MEUR/a	705,8	707,6	664,632	743,665

Vis



Profit potential

Profit potential	Unit	Mean	Median	L95	U95
OptiBase	MEUR	-2,088	-1,609	-20,449	13,591
FixedInvest	MEUR	265,368	265,847	247,007	281,047
OptiInvest	MEUR	680,608	681,177	626,105	756,464

Vis

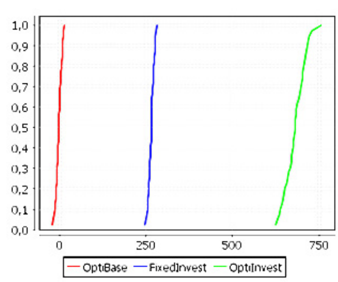


Figure 21. Uncertainty analysis for Board web process OptiBase, FixedInvest, and OptiInvest $\Pi_{\Delta,1\ldots3}$ profit potentials.

4.8 Application of the novel method to web process development

This novel method was developed and applied to web process development during the years 2000-2015. The main idea is that the analysis of profit potentials is applied to focus the development to areas where the greatest profit effects exist. Application of the novel method is carried out as a continuous process consisting of the following steps:

1) Identifying the greatest profit potentials of the existing production lines.
2) New product idea creation based on Step 1).
3) New product idea rough evaluation applying expert data.
4) New product idea focused evaluation applying pilot scale values.
5) New product idea specified evaluation applying production machine values.

Figure 22 presents the idea of continuous application of the novel method to product development in order to create more valuable new products.

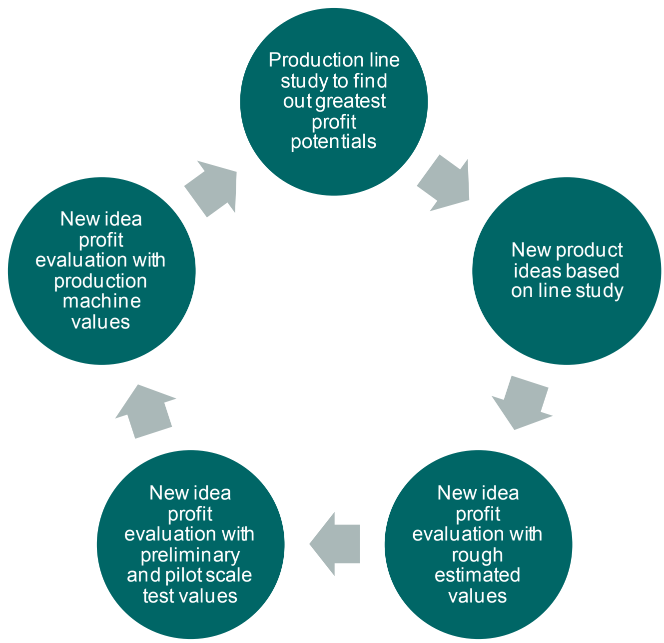


Figure 22. Application of the method to web process development.

4.9 Application of the novel method to other products and services

In this dissertation the novel developed method is applied to different types of web processes. However, the basic idea of the method to establish the factors and equations, which form the profit potential, can be developed to other types of products and services.

Generally, the profit of a product in the current situation is described by Π_c, and the profit potential achieved by improving the product and its production is found by solving the equation:

$$\Pi_{\Delta,3} = \Pi(\hat{x}_v^*, \hat{x}_f) + R(\hat{x}_v) - S(\Pi_c, \hat{x}_v) - C(\hat{x}_v) - \Pi_c. \qquad (62)$$

When the novel method is applied to other products, services and their production systems, the following should be defined:

- Price and cost components related to the product or service.
- Investment components related to the product or service.
- Availability (efficiency) components related to the product or service.
- Production components related to the product or service.
- Connections between the above factors.

When a product is mass-produced directly to consumer markets, the market factors should also be considered. Then, the following equation can be applied:

$$\Pi_t(\mathbf{x}) = y_t(\mathbf{x})\pi_{product,t}(\mathbf{x}) - c_t(\mathbf{x}), \qquad (63)$$

where

$y_t(\mathbf{x})$ = Saleable production (products),
$\pi_{product,t}(\mathbf{x})$ = Profit per product (currency unit / product),
$c_t(\mathbf{x})$ = Cost components (currency unit).

$\pi_{product,t}(\mathbf{x})$ has a connection to product quality i.e. product market price, $r_{pr}(\mathbf{x})$ (currency unit/product), is defined by the quality of the product. Typically there exists quality targets for A quality product and below this quality a customer will pay less for this product. In addition, a production line is connected to quality and product market price. Production amounts over certain limits usually cause an increase in production waste, which limits $y_t(\mathbf{x})$ and also leads to B quality products, which are sold at a lower price.

When there is only a little competition and a high customer value, it is possible to increase $r_{pr}(\mathbf{x})$. Then customer is willing to pay more for this product or service and $\pi_{product,t}(\mathbf{x})$ increases. Therefore, an additional competition factor, $f_{c,t}(\mathbf{x})$, based on market potential analysis can be applied as follows:

$$r_{pr,t}(\mathbf{x}) = r_{prbase,t}(\mathbf{x})f_{c,t}(\mathbf{x}) \qquad (64)$$

where

$r_{prbase,t}(\mathbf{x})$ = product or service base market price during year t (currency unit / product),
$f_{c,t}(\mathbf{x})$ = competition factor during year t.

$r_{prbase,t}(\mathbf{x})$ is defined by the profitability targets of a company. When price $r_{pr,t}(\mathbf{x}) \geq r_{prbase,t}(\mathbf{x})$, it is profitable to produce this product or service. Competition factor can have values above 1 during the years when there is only a little competition (e.g. new product or service with few other producers and/or a well patented product). When competition increases, competition factor can fall below 1. Then production of this product or service should not be continued unless there are other strategic factors justifying this product. Another possible option is to redefine $r_{prbase,t}(\mathbf{x})$ for example based on decreased production costs.

Application of the novel method to new products and services can be further expanded by introducing the following cost component parameters: New market expansion costs, p_{mark}(MEUR/a), $\mathbf{x_v}$, New product or service development costs, p_{prod}(MEUR/a), $\mathbf{x_v}$ and Patent costs, p_{pat}(MEUR/a), $\mathbf{x_v}$. These can be connected to $y_t(\mathbf{x})$, $\pi_{product,t}(\mathbf{x})$ and the investment, $C(\mathbf{x})$, which is optimised to meet the optimised production amounts. The expanded optimisation includes then parameters affecting both the market factors and the production of the product or service.

$$\Pi(p^*_{mark}, p^*_{prod}, p^*_{pat}, \hat{x}_f) = \max_{p_{mark}, p_{prod}, p_{pat}} \Pi(p_{mark}, p_{prod}, p_{pat}, \hat{x}_f) + \frac{R(p_{mark}, p_{prod}, p_{pat}, \hat{x}_f)}{(1+r_t/100)^Y} - S(\Pi_c, p_{mark}, p_{prod}, p_{pat}, \hat{x}_f) - C(p_{mark}, p_{prod}, p_{pat}, \hat{x}_f) \quad (65)$$

Production of different existing and new idea products or services can be analysed applying this novel method. Based on profit potential estimates, development efforts and investments can be targeted to most profitable areas. Improvements can be made to products or services and to production. New products and services produced with new profitable production systems will typically lead to high profits.

The most appropriate targets for this novel method are the products and services, which are sophisticated, and from which the operational production and market data is available. With totally new products, when there is lack of market and production information, the accuracy of this novel method is limited. Then it is important to concentrate much effort on uncertainty and sensitivity analysis. Typically when more profits are expected, the more uncertainty (risk) is tolerated.

5 DISCUSSION

5.1 Results

In this dissertation starting from the profit function (see p.37) the novel method containing different profit potential optimisation levels (see pp.41-44) and sensitivity and uncertainty analysis (see pp.46-47) is developed. Then, this novel method is applied to current and new web process technology (see pp.51-59). As a result, applying the novel method, technologies are optimised and profit potentials $\Pi_{\Delta,1...3}$ are presented. Further, sensitivity and uncertainty related to the profit potentials are defined (pp.60-62).

The input data (see appendix B and C) applied to the calculations is collected from production machines and therefore can be considered as relatively accurate data (p.7, 14, 15, 39, 50). However, for the new technology calculations, the models achieved from pilot tests connecting new components to existing production technology may contain model inaccuracies which are partly unknown until proven on a production scale (p.39, 55, Appendix A).

Sensitivity analysis (p.60) presents sensitivity of profit potential to changes in variables. As mentioned earlier in the method development section (p.47), sensitivity is local sensitivity at the calculation point. Therefore for example back-pressure turbine and an integrated PCC plant investment may indicate too high values at the calculation point where smooth functions are in these models applied to describe sudden changes related to on/off type of steps (turbine or PCC plant in use / not in use). Applying calculations with back-pressure turbine and PCC plant parameters on and off would present with greater accuracy the effect of these on profit.

Uncertainty analysis (pp.61-62) presents, that even applying a relatively great inaccuracy related to new metal belt pressing technology investment parameters together with price uncertainties does not cause a great effect on profit potential estimation result. The new technology profit potential has a high value although uncertainties are included in the calculation.

The application of the novel method continuously as described in Chapter 4.8 would produce more data and further improve accuracy of the method. This can lead to continuous profit improvement as profit potentials are analysed and new profitable products are developed in a continuous process.

New models and new product applications can be included in the profit potential calculations as described in chapter 4.9. Then, this novel method can be applied to different types of products, services, and production systems (pp.64-65). In addition, efforts related to new product or service, production development, marketing and market factors can be included into expanded profit potential calculations (p.65). These parameters are of highest importance if a company is planning on expanding to new market areas with new ideas.

5.2 Validity and reliability

The novel method applies partly the same models and parameters as the existing methods. The data calculated applying the existing models is quite accurate since the existing methods and models are widely studied, tested and accepted by the scientific community. The examples of the existing methods and models are the profit function, and LCC/LCP, profitability and production calculation methods and models.

The difference between the existing methods and the novel method is that the existing methods provide mainly data that can be applied to indirect profit measures calculations or to profit calculations where many of the production technology related parameters are omitted. The novel method applies both the data which can be calculated applying the existing models and the data that can be calculated by introducing new models and the focus of the calculation is directly the profit potential. Therefore it can be said that the novel method compared to the existing methods provides more valid (relevant) data in relation to the research problem. In addition, based on method testing and validation (see Chapters 3.2.1 and 3.7) the results measured by profit and payback period achieved applying the novel method are the same as applying the profitability calculation method for investment calculations.

The reliability (accuracy, repeatability) of the novel method is presented in Chapters 3.6, 4.6, and 4.7 where causality, sensitivity, and uncertainty analyses are discussed and demonstrated through examples. The greatest uncertainties are related to the future price level estimates and to the models describing novel technologies. Therefore it can be recommended that the user of this novel method applies different price scenarios to calculations and updates the models when more test results are available for the novel technologies.

The validity and the reliability of the novel method is described in figure 23. The novel method has better model system coverage and focus on profit potential compared to the existing methods. The ideal method would have a very high coverage of detailed models with great accuracy.

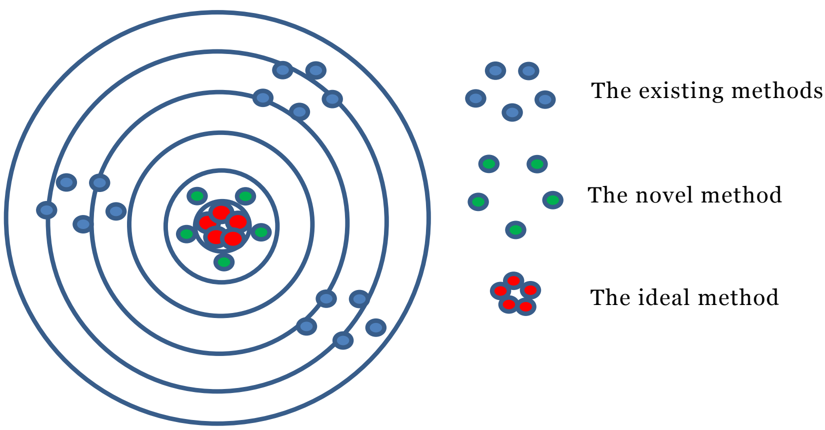


Figure 23. Novel method validity and reliability.

5.3 Research work

This research work was carried out over a relatively long period of time. The advantage related to long research time period is that there is adequate time to gather data, as well as time to test and improve the method. The disadvantage is that the research results are not in this type of monography work presented to the large international scientific community until quite late during the research process. Earlier presentation of results could provide more feedback in early research phases and thus could lead the research on new paths. However, it is to be noted that this method was presented during the research to tens of researchers who focus on simulations, mathematical modeling, web processes and economical calculations. A great amount of feedback was received during the research from them. In addition, an article about the research was published (Pihko (2015)).

Has the research reached the target and has the novel model filled the gap of unknown knowledge in between the known methods and the ideal method (see figure 2)? To begin with, it can be stated that the novel method has more web process and technology related details, factors and input parameters connected to web process profit compared to the existing methods. Secondly, the profit and profit potential is calculated directly as currency units which is a difference and improvement compared to for example distance function approach.

The profit potential levels are extended to further reaching boundaries compared to the existing methods since technology can be optimised to find the solution which produces the highest profit. Therefore, this novel method can bring out significant new possibilities to improve profit. These potentials can be found only partly applying the existing methods.

Applicability of the models to web processes is adequate when the processes are mainly related to press and dryer sections and calenders. However, when the process of interest is in more details related to for example wire sections, head boxes, coating processes and other machine sections, more detailed models describing these processes could be applied.

Applicability of the method to other products, processes and services is described shortly. The basic idea of calculating profit potential at different opmimisation levels should be applicable to other products, services and processes. However, application of the method to other processes would need a comprehensive data collection and model creation to be useful.

Can a reader of this work repeat this research work and come to the same conclusions? The research work consisting of literature research, model development, the models and the input data is presented in this work. Therefore a reader can apply the same research process, and develop, calculate and reach the same results as presented in this dissertation.

5.4 Conclusions and recommendations

Based on the results achieved applying this novel method, the extra profit related to novel pre-pressing, pressing, drying and calendering metal belt technology is very significant. Therefore it can be recommended that development of these processes and components are supported further. In addition, sensitivity analysis presents that an integrated PCC plant and a combined generation of steam and electrical energy in a back-pressure turbine can further improve the profit.

Based on the profit potentials found applying this novel method, it can be claimed that this novel method combined with new technology assessment brings out significant possibilities to improve profitability of paper and board machines. There exists profit potential which can be found applying this novel method and which can benefit both web production and web process machine manufacturing companies in the future.

Continuous application of the method would be important. This would lead to continuous profit growth. After utilising the profit potential related to certain products, parameters and technologies, a new analysis should be carried out to establish the next boundaries, which should be overcome with new solutions.

The equations describing how this novel method can be applied to other products are presented in this dissertation. In addition to this, the more exact models related to other types of products, production systems, and markets can be developed. This would lead to growing understanding of important profit parameters in other industries, products and markets. Then a continuous profit growth related to different types of products, services, and production units in different market areas can be found.

6 SUMMARY

This dissertation focuses on a novel profit potential forecast method. First, a literature review presents the existing methods for profit optimisation and profit improvements. The existing methods can be divided into two categories: methods for direct profit measurement, and indirect methods. On the basis of a literature review, the existing methods inspect only some of the factors related to web process profit improvement possibilities. Currently available methods are generally limited to existing production technology and they do not allow the mathematical treatment of the profit potential of new technologies. In addition, the cause and effect connections between the factors and profit improvements are not formulated. However, it is very important to find the factors and their effects on profit improvements, because this data is crucial to be able to direct machine investments and development efforts efficiently. To be able to find further reaching profit potentials and the factors behind these potentials, a novel method is developed in this dissertation.

In this work, a web process line profit model is developed. Profit boundaries are first defined for the current technology. Then, new concepts: profit potentials at different optimisation levels of increasing complexity are presented. Depending on the optimisation level (Base, OptiBase, FixedInvest, OptiInvest), investments, and modifications to the technology are included in the calculation. Therefore, further reaching profit boundaries are presented. Finally, process causality, sensitivity of profit to changes in parameters and profit optimisation uncertainties are discussed.

In the novel method application chapter, the SC and Board web process technologies are presented. Then the models connecting the technology and profit are presented. The novel method is applied to web process and profit optimisation at different optimisation levels is carried out. The profit potentials, $\Pi_{\Delta,1\ldots3}$, and the development of cash flows over the inspection period are presented graphically. Sensitivity and uncertainties related to calculations are presented for certain input and model parameters. Finally, the basic idea of how to apply this novel method to web process product development and to other products, services and processes is presented.

Based on the results achieved applying this novel method, the extra profit potential related to new pre-pressing, pressing, drying, and calendering metal belt technology is very significant. Therefore it can be recommended that the development of these processes and components is supported in future. In addition, sensitivity analysis presents that an integrated PCC plant and a combined generation of steam and electrical energy in a back-pressure turbine could further improve the profit. Uncertainty analysis can be applied to find out the effect of uncertainties related to different input parameters. Based on the uncertainty analysis, even applying a relatively great inaccuracy to new metal belt pressing technology investment costs together with product and raw material price inaccuracies does not cause a great change in the expected profit potential.

Based on the profit potentials determined, it can be claimed that this novel method applied to new technology brings out significant possibilities to improve profitability of paper and board machines. Applying this novel method, new ideas can be evaluated at early stages of product development and therefore resources can be allocated to the greatest potentials. Therefore R&D investments can be directed efficiently.

The novel method presented in this dissertation can be applied as a continuous process, which leads to continuous profit improvements. In addition, application of the novel method is not limited to web process industry. The models related to the method can be developed to other types of industries and products. If parameters and models related to market factors and the use of resources are included, this novel method can be applied to optimal resource allocation.

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APPENDIX A: PARAMETERS AND MODELS

The models presented here are based on production and pilot machine data, and simulation models presented in Pihko (2000), Heikkilä (1993), Matilainen (2005), Paakki (2009), and Mäntylä (2011). For example, during the years 2000-2012, the novel metal belt pressing and drying technologies were tested and analysed. The testing consisted of pilot scale tests, laboratory tests, simulations and calculations. Based on the test results achieved, the following models were developed and coefficients related to the models were defined. The exact source data behind the models is partly confidential, and therefore not published in this work.

Input parameters

The model requires a set of input parameters which initialise the process. These parameters are denoted by **x** and they are divided into fixed parameters $\mathbf{x_f}$, which remain unchanged during optimisation, and variable parameters $\mathbf{x_v}$, which are tuned to maximise the profit. The numbers of fixed and variable input parameters are given by N_f and N_v, while the total number of parameters is denoted by N.

Each parameter **x**, either fixed or variable, may be either constant over the inspection period or changing annually. The value of a changing parameter at year t is denoted by $\mathbf{x_{f,t}}$ or $\mathbf{x_{v,t}}$, while with constant parameters the subscript t is omitted.

Abbreviations

ref	= reference
sb	= steam box
fs	= felt steamer
mb	= metal belt
prepressmb	= heated metal belt at the wire section
pressmb	= heated metal belt at the press and dryer section
imp	= impingement dryer
dryer	= dryer section
cal	= calender
pcc	= integrated pcc plant
$f(c,x,x_u)$	= differentiable indication function = $2/(1+\exp(-c*x/x_u))-1$, where c=slope coefficient (default value = 100), x=input parameter, value above zero indicates that this process unit is applied to calculation, x_u=upper bound of input parameter

General

Production speed, v(m/min), $\mathbf{x_{v,t}}$

Ref production speed at which speed
ref values are specified, v_{ref}(m/min), $\mathbf{x_f}$

Ref total steam consumption without prepressmb,sb,fs,pressmb,
dryer, $x_{steamref}$(t/h), $\mathbf{x_f}$

Ref total electricity consumption without
prepressmb,fs,pressmb,imp,dryer,cal, x_{elref}(kW), $\mathbf{x_f}$

Ref total gas consumption without imp,cal, x_{gasref}(kW), $\mathbf{x_f}$

Product basis weight, bw(g/m2), $\mathbf{x_f}$

Web width, w(m), $\mathbf{x_f}$[2]

Product moisture after dryer section, dm(%), $\mathbf{x_f}$

High bulk product, $bulky_{on/off}$(0/1), $\mathbf{x_f}$

Efficiency

Maximum available annual operating time, t_{op}(h), $\mathbf{x_{f,t}}$

Planned ref annual shutdown time, $t_{plannedref}$(h), $\mathbf{x_{f,t}}$

Unplanned ref annual shutdown time, $t_{unplannedref}$(h), $\mathbf{x_{f,t}}$

Annual line break time at ref values, $t_{breakref}$(h), $\mathbf{x_{f,t}}$

Production line total broke, broke(%), $\mathbf{x_{f,t}}$

Prices

Product and raw material prices

A quality product market price at speed below v_q, r_{pra}(EUR/t), $\mathbf{x_{f,t}}$

B quality product market price at speed above v_q, r_{prb}(EUR/t), $\mathbf{x_{f,t}}$

Quality change speed, v_q(m/min), $\mathbf{x_f}$

Product transportation price, p_{trans}(EUR/t), $\mathbf{x_{f,t}}$

Product commission fee price, p_{sales}(EUR/t), $\mathbf{x_{f,t}}$

Pulp price, p_{pulp}(EUR/t), $\mathbf{x_{f,t}}$

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[2] If changed, ref input values should be changed accordingly.

Filler, coat, size price, p_{fcs}(EUR/t), $\mathbf{x_{f,t}}$

Chemical price, p_{chem}(EUR/t), $\mathbf{x_{f,t}}$

Water price fresh + effluent, p_{water}(EUR/t), $\mathbf{x_{f,t}}$

Packaging material price, p_{pack}(EUR/t), $\mathbf{x_{f,t}}$

Other operating material price, $p_{otherop}$(EUR/t), $\mathbf{x_{f,t}}$

Energy prices

Electricity price, p_{elmwh}(EUR/MWh), $\mathbf{x_{f,t}}$

Steam ton price, $p_{steamton}$(EUR/t), $\mathbf{x_{f,t}}$

Gas price, p_{gasmwh}(EUR/MWh), $\mathbf{x_{f,t}}$

Back-pressure turbine electricity production variable costs, $p_{turbinemwh}$(EUR/MWh), $\mathbf{x_{f,t}}$

Maintenance and wage prices

Ref maintenance and wearing parts without prepressmb,fs,pressmb,imp,dryer,cal, $p_{parts\&maintref}$(MEUR/a), $\mathbf{x_{f,t}}$

Wages, p_{wages}(MEUR/a), $\mathbf{x_{f,t}}$

Other fixed, $p_{otherfix}$(MEUR/a), $\mathbf{x_{f,t}}$

Investment

Rate of interest, r_t(%),$\mathbf{x_f}$

Inspection period, Y(yrs), $\mathbf{x_f}$

Ref total investment costs without prepressmb,fs,pressmb,imp,dryer,cal,pcc, inv_{ref}(MEUR), $\mathbf{x_f}$

Prepressmb investment, $invprepressmb_{on/off}$(0/1), $\mathbf{x_f}$

Felt steamer investment, $invfs_{on/off}$(0/1), $\mathbf{x_f}$

Pressmb investment, $invpressmb_{on/off}$(0/1), $\mathbf{x_f}$

Impingement dryer investment, $invimp_{on/off}$, $\mathbf{x_f}$

Dryer section investment, $invdryer_{on/off}$(0/1), $\mathbf{x_f}$

Dryer section machine hall investment, $invdryermh_{on/off}$(0/1), $\mathbf{x_f}$

Pressmb precalender investment, $invcal_{mbpre}$(0/1), $\mathbf{x_f}$

mb finishing calender investment, $invcal_{mbfin}$(0/1), $\mathbf{x_f}$

Soft finishing calender investment, $invcal_{softfin}$(0/1), $\mathbf{x_f}$

Hard finishing calender investment, $invcal_{hardfin}$(0/1), $\mathbf{x_f}$

PCC production investment, $invpcc_{on/off}$(0/1), $\mathbf{x_f}$

Investment residual value after inspection period, $R(x_v,x_f)$(MEUR), $\mathbf{x_f}$

Investment shutdown, inv_{sd}(h), $\mathbf{x_f}$

Process

Press

Ref dryness before steam box, d_{sbref}(%),$\mathbf{x_{f,t}}$

Ref dryness after press concept
at design nip loads without sb,fs,pressmb, $d_{pressref}$(%), $\mathbf{x_{f,t}}$

Steam box steam, x_{sb}(t/h), $\mathbf{x_{v,t}}$

Felt steamer steam, x_{fs}(t/h), $\mathbf{x_{v,t}}$

Last shoe press nip load[3], $f_{lastnip}$(kN/m), $\mathbf{x_{v,t}}$

Prepressmb effective length, $l_{prembeff}$(m), $\mathbf{x_f}$ **or** $\mathbf{x_v}$

Pressmb effective length, l_{mbeff}(m), $\mathbf{x_f}$ **or** $\mathbf{x_v}$

Dryer

Impingement effective drying length, l_{imp}(m), $\mathbf{x_f}$ **or** $\mathbf{x_v}$

Tappi drying rate, $c_{tappidr}$(kgH2O/m2h), $\mathbf{x_f}$

Calender

Pressmb precalender nips, $n_{mbprenips}$(pcs), $\mathbf{x_f}$ **or** $\mathbf{x_v}$

mb finishing calender nips, $n_{mbfinnips}$(pcs), $\mathbf{x_f}$ **or** $\mathbf{x_v}$

Soft finishing calender nips, $n_{softfinnips}$(pcs), $\mathbf{x_f}$ **or** $\mathbf{x_v}$

Hard finishing calender nips, $n_{hardfinnips}$(pcs), $\mathbf{x_f}$ **or** $\mathbf{x_v}$

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[3] In case of roll nip adjust based on target dryness level after press %.

PCC plant and turbine

CO_2 concentration in pcc production, c_{pcc}(%),**x_f or x_v**

Back-pressure turbine, $turbine_{on/off}$(0/1), **x_f**

Outputs

Models A_i for process quantities q_i

General

Basis weight required to produce product, $bw_{required}$(g/m2)	$=(0{,}005*f_{lastnip}+bw-0{,}05*bw*f(c,n_{mbfinnips}, n_{mbfinnips,u})-5+((d_{pressbw}-(-3*10^{-6}*f_{lastnip}^2+0{,}008*f_{lastnip}-5)-d_{pressref})*0{,}5))*f(c,bulky_{on/off},bulky_{on/off,u})+(1-f(c,bulky_{on/off},bulky_{on/off,u}))*bw$
Bone dry production, $y_{bonedry}$(kg/s)	$= v*w*bw_{required}*60/1000/1000*(100-dm)/100/3{,}6$
Bone dry production(bw), $y_{bonedrybw}$(kg/s)	$= v*w*bw*60/1000/1000*(100-dm)/100/3{,}6$
Product market price, r_{pr}(EUR/t)	= if $v \le v_q-d_v$ then $r_{pr}=r_{pra}$, if $v \ge v_q+d_v$ then $r_{pr}=r_{prb}$, if $v_q-d_v<v<v_q+d_v$ then $r_{pr}=c_3*v^3 + c_2*v^2 + c_1*v + c_0$ where c_i solves the equation system $c_3(v_q-d_v)^3+ c_2(v_q-d_v)^2+ c_1(v_q-d_v)+ c_0= r_{pra}$ $c_3(v_q+d_v)^3+ c_2(v_q+d_v)^2+ c_1(v_q+d_v)+ c_0= r_{prb}$ $3*c_3(v_q-d_v)^2+ 2*c_2(v_q-d_v)+ c_1=0$ $3*c_3(v_q+d_v)^2+ 2*c_2(v_q+d_v)+ c_1=0$

Process

Press

Dryness at steam box, d_{sb}(%)	$= d_{sbref} +0{,}35*(v_{ref}-v/100)$
Water at steam box, sb_{water}(kg/s)	$= y_{bonedry}(1-d_{sb}/100)/(d_{sb}/100)$
Water at steam box(bw), $sb_{waterbw}$(kg/s)	$= y_{bonedrybw}(1-d_{sb}/100)/(d_{sb}/100)$
Web temp after sb, t_{websb}(°C)	$=-0{,}25*(x_{SB}*11/sb_{water})^2+4{,}92*(x_{SB}*11/sb_{water})+43{,}1$

Web temp after steam box(bw),

$t_{websbbw}$(C)	$=-0,25*(x_{SB}*11/sb_{waterbw})^\wedge2+4,92*(x_{SB}*11/sb_{waterbw})+43,1$
Felt temp, t_{felt} (°C)	$=-0,14*(x_{fs}*11/sb_{water})^\wedge2+5,5*(x_{fs}*11/sb_{water})+40+((t_{websb}-40)*0,5)$
Felt temp(bw), t_{feltbw} (°C)	$=-0,14*(x_{fs}*11/sb_{waterbw})^\wedge2+5,5*(x_{fs}*11/sb_{waterbw})+40+((t_{websbbw}-40)*0,5)$
Ref felt temp, $t_{feltref}$(°C)	$= 40+((t_{websb}-40)*0,5)$
Ref felt temp(bw), $t_{feltrefbw}$(°C)	$= 40+((t_{websbbw}-40)*0,5)$
Water amount coefficient, c_{water}(-)	$= (sb_{water}/w)/1,93$
Water amount coefficient(bw), $c_{waterbw}$(-)	$= (sb_{waterbw}/w)/1,93$
Web temp after press, $t_{webpress}$(°C)	$=((0,298*c_{water}{}^\wedge2)-9,587*c_{water}+101,1)*f(c,l_{mbeff}, l_{mbeff,u})+((0,423*t_{websb}+21,41+(t_{felt}-t_{feltref})*0,3)*COS(3,14/2*(f(c, l_{mbeff}, l_{mbeff,u}))))$
Web temp after press(bw), $t_{webpressbw}$(°C)	$=((0,298*c_{waterbw}{}^\wedge2)-9,587*c_{waterbw}+101,1)*f(c,l_{mbeff}, l_{mbeff,u})+((0,423*t_{websbbw}+21,41+(t_{feltbw}-t_{feltrefbw})*0,3)*COS(3,14/2*(f(c, l_{mbeff}, l_{mbeff,u}))))$
Ref web temp after press, $t_{webpressref}$(°C)	$= 0,423*t_{websb} + 21,41$
Ref web temp after press(bw), $t_{webpressrefbw}$(°C)	$= 0,423*t_{websbbw} + 21,41$
Dryness after press, d_{press}(%)	$=(t_{webpress}-t_{webpressref})*0,15+(t_{felt}-t_{feltref})*0,1+(t_{websb}-42,83)*0,15+d_{pressref}-3*10^\wedge-6*f_{lastnip}{}^\wedge2+0,008* f_{lastnip}-5+0,35*(v_{ref}-v)/100$
Dryness after press(bw), $d_{pressbw}$(%)	$=(t_{webpressbw}-t_{webpressrefbw})*0,15+(t_{feltbw}-t_{feltrefbw})*0,1+(t_{websbbw}-42,83)*0,15+d_{pressref}-3*10^\wedge-6*f_{lastnip}{}^\wedge2+0,008* f_{lastnip}-5+0,35*(v_{ref}-v)/100$

Dryer

Dryness after press+pressmb+imp, d_{mb+imp}(%)	$=d_{press}+(l_{mbeff}/2+l_{imp}/2)*5,28*exp(-0,81*c_{water})+((t_{webpress}-39)/40)*1,533*c_{water}$ ^-0,25
Water to be evaporated after press+pressmb+imp, $y_{evwater}$(kg/s)	$= y_{bonedry}*(1-d_{mb+imp}/100)/(d_{mp+imp}/100)-y_{bonedry}*(dm/100)/(1-dm/100)$
Dryer cylinders, cyl_{dryer}(pcs)	$= 3600*y_{evwater}/(1,83*3,141*c_{tappidr}*w)*(0,83*f(c,l_{mbeff}, l_{mbeff,u})+(1-f(c,l_{mbeff}, l_{mbeff,u})))$
Dryer section length, l_{dryer}(m)	$= cyl_{dryer}*2,1$

Energy, press, dryer, cal

Prepressmb steam, x_{premb}(t/h)	$= l_{prembeff}*0,24*w/5,7*3,6$
Pressmb steam, x_{mb}(t/h)	$= l_{mbeff}*0,24*w/5,7*3,6$
Impingement dryer gas consumption, x_{gasimp}(kW)	$= l_{imp}*420*w/5,7$
Dryer section steam, x_{dryer}(t/h)	$= y_{evwater}*2260/0,9*3,6/2132$
Calender gas consumption, x_{gascal}(kW)	$=(n_{mbprenips}*w*64+n_{mbfinnips}*w*200+n_{softfinnips}*w*64+n_{hardfinnips}*w/11*900)*(v/1400)$^1,5

Investment

Investment coefficient, c_{vw}(-)	$= (0,463*exp(0,773*(w/5,7)))*v/v_{ref}$
Felt steamer investment, Inv_{fs}(MEUR)	$= w/10*1*f(c,invfs_{on/off}, invfs_{on/off,u})$
Prepressmb investment, inv_{premb}(MEUR)	$= (l_{prembeff}*0,2*0,22+6)*c_{vw}*f(c,invprepressmb_{on/off}, invprepressmb_{on/off,u})$
Pressmb investment, inv_{mb}(MEUR)	= (l_{mbeff}*0,2*0,22[4]+4[5])*c_{vw} $*f(c,invpressmb_{on/off}, invpressmb_{on/off,u})$

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[4] 0,2*0,22=0,044 is Pressmb coefficient c0, $\mathbf{x_f}$

[5] 4 is Pressmb coefficient c1, $\mathbf{x_f}$

Impingement dryer investment, inv_{imp}(MEUR) $= l_{imp}*0,28*c_{vw}*f(c,invimp_{on/off}, invimp_{on/off,u})$

Dryer section investment, inv_{dryer}(MEUR) $= l_{dryer}*0,22*c_{vw}*f(c,invdryer_{on/off}, invdryer_{on/off,u})$

Dryer section machine hall investment, $inv_{dryermh}$(MEUR) $= l_{dryer}*0,13*c_{vw}*f(c,invdryermh_{on/off}, invdryermh_{on/off,u})$

Calender investment, inv_{cal}(MEUR) $= c_{vw}*(n_{mbprenips}*1,7*f(c,invcal_{mbpre},invcal_{mbpre,u}) + n_{mbfinnips}*8*f(c,invcal_{mbfin},invcal_{mbfin,u}) + n_{softfinnips}*3,5*f(c,invcal_{softfin},invcal_{softfin,u}) + n_{hardfinnips}*1,3*f(c,invcal_{hardfin},invcal_{hardfin,u}))$

PCC plant investment, inv_{pcc}(MEUR) $= x_{gas}/2900*(-0,45*c_{pcc}+9,8) * f(c,invpcc_{on/off},invpcc_{on/off,u})$

Total investment costs, C(MEUR) $=inv_{ref}+inv_{premb}+inv_{fs}+inv_{mb}+inv_{imp}+inv_{dryer}+inv_{dryermh}+inv_{cal}+inv_{pcc}$

Efficiency

Annual planned shutdowns, $t_{planned}$(h/a) $= t_{plannedref}*(v/v_{ref})$^1,5

Annual unplanned shutdowns, $t_{planned}$(h/a) $= t_{plannedref}*(v/v_{ref})$^0,7

Annual break time, t_{break}(h/a) $= (v/v_{ref})^{5,6}*t_{breakref}*1*(d_{mp+imp}/d_{pressref})$^-5

Time efficiency, η_{time}(%) $= t_{op}-(t_{planned}+t_{break}+t_{unplanned})/t_{op}*100$

Total efficiency, η_{tot}(%) $= \eta_{time}*$ broke

Production

Momentary production, y_h(t/h) = $v*w*bw/1000000*60$

Annual production, y_t(t/a) = $v*w*bw*60/10^6*t_{op}*\eta_{tot}/100$

Annual production($bw_{required}$), $y_{tbwrequired}$(t/a) = $v*w*bw_{required}*60/10^6*t_{op}*\eta_{tot}/100$

Energy, total

Total steam consumption, x_{steam}(t/h) = $x_{premb}+x_{sb}+x_{fs}+x_{mb}+x_{dryer}+x_{steamref}$

Total gas consumption, x_{gas}(kW) = $x_{gasref}*(v/v_{ref})^\wedge 1{,}5+x_{gasimp}+x_{gascal}$

Total electricity consumption, x_{el}(kW)

$$
\begin{aligned}
=\ & x_{elref}*(v/v_{ref})^\wedge 1{,}5 \\
& -200*w/10*(v/1600)^\wedge 1{,}5*f(c,invfs_{on/off}, invfs_{on/off,u}) \\
& +250*w/10*(v/1350)^\wedge 1{,}5*f(c,invpressmb_{on/off}, invpressmb_{on/off,u}) \\
& +250*w/10*(v/1350)^\wedge 1{,}5*f(c,invprepressmb_{on/off}, invprepressmb_{on/off,u}) \\
& +600*w/10*l_{imp}/10 \\
& +l_{dryer}*2100/50*w/10*(v/1800)^\wedge 1{,}5 \\
& +n_{mbprenips}*w/10*750*(v/1750)^\wedge 1{,}5 \\
& +n_{mbfinnips}*w/10*750*(v/1750)^\wedge 1{,}5 \\
& +n_{softfinnips}*w/10*750*(v/1750)^\wedge 1{,}5 \\
& +n_{hardfinnips}*w/11*112*(v/1400)^\wedge 1{,}5
\end{aligned}
$$

Energy prices per mass unit of product

Steam, p_{steam}(EUR/t) = $x_{steam}*p_{steamton}/y_h$

Electricity, p_{el}(EUR/t) = $x_{el}/1000*p_{elmwh}/y_h$

Gas, p_{gas}(EUR/t) = $x_{gas}/1000*p_{gasmwh}/y_h$

Profits and expenses

Profit per mass unit of product, π_{mass}(EUR/t)

$$= r_{pr}-(p_{trans}+p_{sales}+p_{pulp}+p_{fcs}+p_{chem}+p_{water}+p_{pack}+p_{otherop}+p_{el}+p_{steam}+p_{gas})$$

Break expenses, p_{breaks}(MEUR/a)

$$=t_{break}*y_h*(p_{chem}+p_{water}+p_{el}+p_{steam})/10\text{^}6$$

Broke expenses, p_{broke} (MEUR/a)

$$=t_{op}*(\eta_{time}/100)*y_h*(broke/100)*(p_{chem}+p_{water}+p_{el}+p_{steam}+p_{gas})/10\text{^}6$$

Maintenance and wearing part expenses, $p_{parts\&maint}$(MEUR/a)

$$= p_{parts\&maintref}*v/v_{ref}$$
$$+1*w/10*\ f(c,invprepressmb_{on/off}, invprepressmb_{on/off,u})*v/1500$$
$$+0{,}05*\ f(c,invfs_{on/off}, invfs_{on/off,u})*v/1500$$
$$+1*w/10*\ f(c,invpressmb_{on/off}, invpressmb_{on/off,u})*v/1500$$
$$+0{,}05*w/10*\ f(c,invimp_{on/off}, invimp_{on/off,u})$$
$$+cyl_{dryer}/50*0{,}5*w/10*v/1850$$
$$+n_{hardfinnips}*0{,}6/18*w/10*v/1850$$
$$+(n_{mbprenips}+n_{softfinnips})*0{,}1*w/10*v/1600$$
$$+n_{mbfinnips}*1{,}5*w/10*v/1000$$

Turbine profit, $\pi_{turbine}$(MEUR/a)

$$= (x_{steam}-x_{steamref})*0{,}602*0{,}92*8300*(p_{elect}-p_{turbine})/10\text{^}6 * f(c,turbine_{on/off}, turbine_{on/off,u})$$

PCC profit, π_{pcc}(MEUR/a)

$$= x_{gas}/2900*(0{,}05*c_{pcc}+1{,}3) * f(c,invpcc_{on/off}, invpcc_{on/off,u})$$

Annual profit, π_t(MEUR/a)

$$=y_t*r_{pr}-y_{tbwrequired}*(p_{trans}+p_{sales}+p_{pulp}+p_{fcs}+p_{chem}+p_{water}+p_{pack}+p_{otherop}+p_{el}+p_{steam}+p_{gas})-(p_{breaks}+p_{broke}+p_{parts\&maint}+p_{wages}+p_{otherfix})+\pi_{pcc}+\pi_{turbine}$$

Investment shutdown profit loss, S(MEUR)

$$=inv_{sd}/t_{op}*(y_t*\pi_{mass}/10\text{^}6-(p_{breaks}+p_{broke}+p_{parts\&maint}))$$

Time value of future cash flows

$$\Pi(x) = \sum_{t=1}^{Y} \frac{\pi_t(x)}{(1+r_t/100)^t}$$

Current technology profit potential

$$\Pi_{\Delta,1} = \Pi(x_v^*, x_f) - \Pi_c$$

$$\Pi^*(T, x_f) = max_{x_v} \Pi(x_v, x_f)$$

subject to

$$Le_i \le (x_v)_i, \quad (x_v)_i \le Ue_i,$$

Optimisation with respect to speed v applying x_f values according to the current technology:

$$\Pi(v^*, x_f) = \max_v \Pi(v, x_f)$$

subject to

1200 m/min≤v, v≤1500 m/min

Fixed investment profit potential

$$\Pi_{\Delta,2} = \Pi(x_v^*, x_f) + \frac{R(x_f)}{(1+r_t/100)^Y} - S(\Pi_c, x_f) - C(x_f) - \Pi_c$$

Optimisation with respect to speed v and last nip load $f_{lastnip}$ applying x_f values according to invested technology:

$$\Pi(v^*, \mathrm{f}^*_{\mathrm{lastnip}}, x_f) = \max_{v, f_{lastnip}} \Pi(v, f_{lastnip}, x_f)$$

subject to

1200 m/min≤v, v≤1800 m/min
200 kN/m≤$f_{lastnip}$, $f_{lastnip}$ ≤1200 kN/m

Variable investment profit potential

$$\Pi_{\Delta,3} = \Pi(\hat{x}_v^*, \hat{x}_f) + \frac{R(\hat{x}_v, \hat{x}_f)}{(1+r_t/100)^Y} - S(\Pi_c, \hat{x}_v, \hat{x}_f) - C(\hat{x}_v, \hat{x}_f) - \Pi_c$$

Optimisation with respect to speed v and metal belt effective length l_{mbeff} applying x_f values according to the invested technology:

Hat above a parameter emphasises a changed variable set. Status of the parameter l_{mbeff} is changed from fixed to variable parameter.

$$\Pi(v^*, l^*_{mbeff}, \hat{x}_f) = \max_{v, l_{mbeff}} \Pi(v, l_{mbeff}, \hat{x}_f) + R(v, l_{mbeff}, \hat{x}_f) - S(\Pi_c, v, l_{mbeff}, \hat{x}_f) - C(v, l_{mbeff}, \hat{x}_f)$$

subject to

$1200 \text{ m/min} \le v,\ v \le 2000 \text{ m/min}$
$0 \text{ m} \le l_{mbeff},\ l_{mbeff} \le 80\text{m}$

Profit improvement (MEUR) per parameter unit

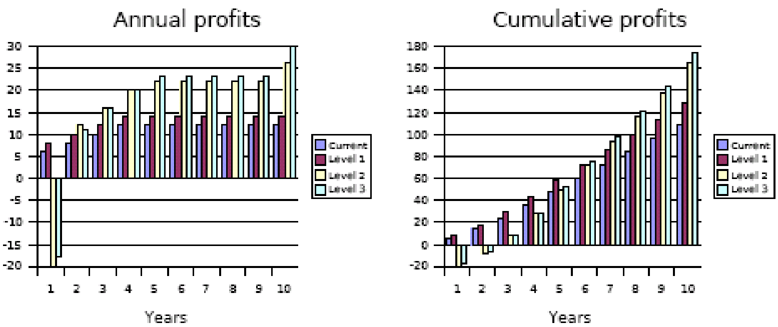
$$\frac{d\,\Pi(x)}{d\,x_v}$$

Profit improvement with respect to change in speed v:

$$\frac{d\Pi(x)}{dv}$$

Graphics

Annual cash flows applying r_t



APPENDIX B: SC WEB PROCESS INITIAL INPUT PARAMETER VALUES

Parameter	Unit	Min	Max	1	2	3	4	5	6	7	8	9	10
Base, OptiBase													
General													
Ref total electricity consumption without prepressmb, fs, pressmb, imp, dryer, cal	kW	0	15000	9415.0	9415.0	9415.0	9415.0	9415.0	9415.0	9415.0	9415.0	9415.0	9415.0
Product moisture after dryer section	%	2	10	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Product basis weight	g/m2	45	55	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0
Ref total steam consumption without prepressmb, sb, fs, pressmb, dryer	t/h	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
High bulk product	on/off	0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rate of interest	%	100	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ref total gas consumption	kW	0	6000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production speed	m/min	1200	2000	1250.0	1250.0	1250.0	1250.0	1250.0	1250.0	1250.0	1250.0	1250.0	1250.0
Web width	m	5	15	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
Ref production speed	m/min	1200	2000	1250.0	1250.0	1250.0	1250.0	1250.0	1250.0	1250.0	1250.0	1250.0	1250.0
Efficiency													
Production line total broke	%	0	50	9,7	9,7	9,7	9,7	9,7	9,7	9,7	9,7	9,7	9,7
Planned ref annual shutdown time	h	0	1000	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0
Maximum available annual operating time	h	0	8760	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0
Unplanned ref annual shutdown time	h	0	1000	129.0	129.0	129.0	129.0	129.0	129.0	129.0	129.0	129.0	129.0
Annual line break time at ref values	h	0	500	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0	400.0
Costs													
Other fixed price	MEUR/a	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ref maintenance and wearing parts price without prepressmb, fs, pressmb, imp, dryer,	MEUR/a	0	10	4,4	4,4	4,4	4,4	4,4	4,4	4,4	4,4	4,4	4,4
Wages price	MEUR/a	0	20	10,4	10,4	10,4	10,4	10,4	10,4	10,4	10,4	10,4	10,4
Prices													
Chemical price	EUR/t	0	1000	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0
Pulp price	EUR/t	0	1000	211.0	211.0	211.0	211.0	211.0	211.0	211.0	211.0	211.0	211.0
Other operating material	EUR/t	0	1000	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Product comission fee price	EUR/t	0	100	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
A quality product market price at speed below	EUR/t	0	1000	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0
Water price fresh and effluent	EUR/t	0	1000	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
B quality product market price at speed above vq	EUR/t	0	1000	570.0	570.0	570.0	570.0	570.0	570.0	570.0	570.0	570.0	570.0
Packaging material	EUR/t	0	1000	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Filler, coat, size price	EUR/t	0	1000	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Quality change speed	m/min	1200	2000	1400.0	1400.0	1400.0	1400.0	1400.0	1400.0	1400.0	1400.0	1400.0	1400.0
Product transportation price	EUR/t	0	100	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Energy prices													
Steam ton price	EUR/t	0	100	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Gas price	EUR/MWh	0	100	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Electricity price	EUR/MWh	0	100	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Back-pressure turbine electricity production variable costs	EUR/MWh	0	1000	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Press													
Felt steamer steam	t/h	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pressmb drying effective length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Steam box steam	t/h	0	10	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5
Prepressmb drying effective length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Last press nip load	kN/m	100	1500	470.0	470.0	470.0	470.0	470.0	470.0	470.0	470.0	470.0	470.0
Ref dryness after press concept at design nip loads without sb, fs, pressmb	%	0	70	46.75	46.75	46.75	46.75	46.75	46.75	46.75	46.75	46.75	46.75
Ref dryness before steam box	%	0	60	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
Web temperature after wire section	C	20	80	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83
Dryer													
Tappi drying rate	kgH20/m^2h	0	30	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Impingement effective drying length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Calender													
Pressmb precalender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hard finishing calender nips	pcs	0	20	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Soft finishing calender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
mb finishing calender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Parameter	Unit	Min	Max	1	2	3	4	5	6	7	8	9	10
FixedInvest													
General													
Ref total steam consumption without prepressmb, sb, fs, pressmb, dryer	t/h	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Product basis weight	g/m2	45	55	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0
Production speed	m/min	1200	2000	1850.0	1850.0	1850.0	1850.0	1850.0	1850.0	1850.0	1850.0	1850.0	1850.0
Rate of interest	%	0	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Product moisture after dryer section	%	2	10	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Ref total gas consumption	kW	0	6000	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ref production speed	m/min	1200	2000	1850.0	1850.0	1850.0	1850.0	1850.0	1850.0	1850.0	1850.0	1850.0	1850.0
High bulk product	on/off	0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ref total electricity consumption without prepressmb, fs, pressmb, imp, dryer, cal	kW	0	30000	20000.0	20000.0	20000.0	20000.0	20000.0	20000.0	20000.0	20000.0	20000.0	20000.0
Web width	m	5	15	9,3	9,3	9,3	9,3	9,3	9,3	9,3	9,3	9,3	9,3
Efficiency													
Unplanned ref annual shutdown time	h	0	1000	134.0	134.0	134.0	134.0	134.0	134.0	134.0	134.0	134.0	134.0
Planned ref annual shutdown time	h	0	1000	136.0	136.0	136.0	136.0	136.0	136.0	136.0	136.0	136.0	136.0
Production line total broke	%	0	50	9,7	9,7	9,7	9,7	9,7	9,7	9,7	9,7	9,7	9,7
Annual line break time at ref values	h	0	500	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
Maximum available annual operating time	h	0	8760	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0
Costs													
Wages price	MEUR/a	0	20	10,4	10,4	10,4	10,4	10,4	10,4	10,4	10,4	10,4	10,4
Other fixed price	MEUR/a	0	10	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
without prepressmb, fs, pressmb, imp, dryer, cal	MEUR/a	0	10	5,4	5,4	5,4	5,4	5,4	5,4	5,4	5,4	5,4	5,4
Prices													
Pulp price	EUR/t	0	1000	211.0	211.0	211.0	211.0	211.0	211.0	211.0	211.0	211.0	211.0
Product comission fee price	EUR/t	0	100	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Chemical price	EUR/t	0	1000	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0
B quality product market price at speed above vq	EUR/t	0	1000	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0
A quality product market price at speed below vq	EUR/t	0	1000	630.0	630.0	630.0	630.0	630.0	630.0	630.0	630.0	630.0	630.0
Quality change speed	m/min	1200	2000	1900.0	1900.0	1900.0	1900.0	1900.0	1900.0	1900.0	1900.0	1900.0	1900.0
Packaging material	EUR/t	0	1000	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Other operating material	EUR/t	0	1000	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Product transportation price	EUR/t	0	100	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Filler, coat, size price	EUR/t	0	1000	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Water price fresh and effluent	EUR/t	0	1000	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
Energy prices													
Gas price	EUR/MWh	0	100	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Steam ton price	EUR/t	0	100	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Back-pressure turbine electricity production variable costs	EUR/MWh	0	1000	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Electricity price	EUR/MWh	0	100	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Press													
Prepressmb drying effective length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ref dryness after press concept at design nip loads without sb, fs, pressmb	%	0	70	49.0	49.0	49.0	49.0	49.0	49.0	49.0	49.0	49.0	49.0
Ref dryness before steam box	%	0	60	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
Felt steamer steam	t/h	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Last press nip load	kN/m	500	1500	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
Steam box steam	t/h	0	10	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5
Pressmb drying effective length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dryer													
Impingement effective drying length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tappi drying rate	kgH20/m^2h	0	30	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Calender													
Pressmb precalender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
mb finishing calender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hard finishing calender nips	pcs	0	20	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Soft finishing calender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Investment													
Ref total investment costs without prepressmb, fs, pressmb, imp, dryer, cal, pcc plant	MEUR	0	300	220.0	220.0	220.0	220.0	220.0	220.0	220.0	220.0	220.0	220.0
Pressmb precalender investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dryer section machine hall investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Investment residual value after inspection period	MEUR	0	100	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
mb finishing calender investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dryer section investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Investment shutdown	h	0	1000	672.0	672.0	672.0	672.0	672.0	672.0	672.0	672.0	672.0	672.0
Soft finishing calender investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Impingement dryer investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pressmb investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Prepressmb investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Felt steamer investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hard finishing calender investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PCC production investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Parameter	Unit	Min	Max	1	2	3	4	5	6	7	8	9	10
OptiInvest													
General													
Product moisture after dryer section	%	2	10	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
High bulk product	on/off	0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Product basis weight	g/m2	45	55	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0
Web width	m	5	15	9,28	9,28	9,28	9,28	9,28	9,28	9,28	9,28	9,28	9,28
Ref production speed	m/min	1200	2500	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0
Ref total electricity consumption without prepressmb, fs, pressmb, imp, dryer, cal	kW	0	30000	18000.0	18000.0	18000.0	18000.0	18000.0	18000.0	18000.0	18000.0	18000.0	18000.0
Rate of interest	%	0	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production speed	m/min	1200	2000	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0	2000.0
Ref total gas consumption	kW	0	6000	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Ref total steam consumption without prepressmb, sb, fs, pressmb, dryer	t/h	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Efficiency													
Production line total broke	%	0	50	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Unplanned ref annual shutdown time	h	0	1000	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
Maximum available annual operating time	h	0	8760	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0	8578.0
Annual line break time at ref values	h	0	500	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
Planned ref annual shutdown time	h	0	1000	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0	64.0
Costs													
Other fixed price	MEUR/a	0	10	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Wages price	MEUR/a	0	20	10,4	10,4	10,4	10,4	10,4	10,4	10,4	10,4	10,4	10,4
Ref maintenance and wearing parts price without prepressmb, fs, pressmb, imp, dryer,	MEUR/a	0	10	4,4	4,4	4,4	4,4	4,4	4,4	4,4	4,4	4,4	4,4
Prices													
Chemical price	EUR/t	0	1000	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0	56.0
Water price fresh and effluent	EUR/t	0	1000	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
Product transportation price	EUR/t	0	100	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Pulp price	EUR/t	0	1000	195.0	195.0	195.0	195.0	195.0	195.0	195.0	195.0	195.0	195.0
Quality change speed	m/min	1200	2500	2200.0	2200.0	2200.0	2200.0	2200.0	2200.0	2200.0	2200.0	2200.0	2200.0
A quality product market price at speed below vq	EUR/t	0	1000	630.0	630.0	630.0	630.0	630.0	630.0	630.0	630.0	630.0	630.0
Packaging material	EUR/t	0	1000	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Product comission fee price	EUR/t	0	100	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Filler, coat, size price	EUR/t	0	1000	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
Other operating material	EUR/t	0	1000	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
B quality product market price at speed above vq	EUR/t	0	1000	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0	600.0
Energy prices													
Steam ton price	EUR/t	0	100	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Gas price	EUR/MWh	0	100	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Electricity price	EUR/MWh	0	100	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Back-pressure turbine electricity production variable costs	EUR/MWh	0	1000	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Press													
Pressmb drying effective length	m	0	30	26.205109	9	9	9	9	9	9	9	9	9
Ref dryness before steam box	%	0	60	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Prepressmb drying effective length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ref dryness after press concept at design nip loads without sb, fs, pressmb	%	0	70	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0	52.0
Felt steamer steam	t/h	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Last press nip load	kN/m	500	1500	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
Steam box steam	t/h	0	10	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5
Dryer													
Tappi drying rate	kgH20/m^2h	0	30	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0
Impingement effective drying length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Calender													
Hard finishing calender nips	pcs	0	10	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Pressmb precalender nips	pcs	0	10	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
mb finishing calender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Soft finishing calender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Investment													
Prepressmb investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Felt steamer investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Investment residual value after inspection period	MEUR	0	100	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Investment shutdown	h	0	800	420.0	420.0	420.0	420.0	420.0	420.0	420.0	420.0	420.0	420.0
PCC production investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Impingement dryer investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pressmb precalender investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
mb finishing calender investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hard finishing calender investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Ref total investment costs without prepressmb, fs, pressmb, imp, dryer, cal, pcc plant	MEUR	0	300	220.0	220.0	220.0	220.0	220.0	220.0	220.0	220.0	220.0	220.0
Dryer section machine hall investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Dryer section investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Soft finishing calender investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pressmb investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

APPENDIX C: BOARD WEB PROCESS INITIAL INPUT PARAMETER VALUES

Parameter	Unit	Min	Max	1	2	3	4	5	6	7	8	9	10
Base, OptiBase													
General													
Ref total steam consumption without prepressmb, sb, fs, pressmb, dryer	t/h	0	50	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Ref total gas consumption	kW	0	6000	2200.0	2200.0	2200.0	2200.0	2200.0	2200.0	2200.0	2200.0	2200.0	2200.0
Product moisture after dryer section	%	2	10	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Ref production speed	m/min	300	2000	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0
Rate of interest	%	100	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Production speed	m/min	300	2000	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0
Product basis weight	g/m2	45	350	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0
High bulk product	on/off	0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Web width	m	5	15	8,11	8,11	8,11	8,11	8,11	8,11	8,11	8,11	8,11	8,11
Ref total electricity consumption without	kW	0	30000	15000.0	15000.0	15000.0	15000.0	15000.0	15000.0	15000.0	15000.0	15000.0	15000.0
Efficiency													
Unplanned ref annual shutdown time	h	0	1000	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0	180.0
Maximum available annual operating time	h	0	8760	8640.0	8640.0	8640.0	8640.0	8640.0	8640.0	8640.0	8640.0	8640.0	8640.0
Planned ref annual shutdown time	h	0	1000	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
Production line total broke	%	0	50	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Annual line break time at ref values	h	0	500	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Costs													
Other fixed price	MEUR/a	0	10	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Wages price	MEUR/a	0	20	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
without prepressmb, fs, pressmb, imp, dryer, cal	MEUR/a	0	10	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Prices													
Other operating material	EUR/t	0	1000	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Pulp price	EUR/t	0	1000	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
Quality change speed	m/min	300	2000	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
B quality product market price at speed above vq	EUR/t	0	1000	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0
A quality product market price at speed below	EUR/t	0	1000	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0
Packaging material	EUR/t	0	1000	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Product comission fee price	EUR/t	0	100	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Product transportation price	EUR/t	0	100	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Water price fresh and effluent	EUR/t	0	1000	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
Filler, coat, size price	EUR/t	0	1000	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0
Chemical price	EUR/t	0	1000	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Energy prices													
Back-pressure turbine electricity production variable costs	EUR/MWh	0	1000	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Steam ton price	EUR/t	0	100	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
Gas price	EUR/MWh	0	100	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Electricity price	EUR/MWh	0	100	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
Press													
Felt steamer steam	t/h	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ref dryness after press concept at design nip loads without sb, fs, pressmb	%	0	70	49.0	49.0	49.0	49.0	49.0	49.0	49.0	49.0	49.0	49.0
Last press nip load	kN/m	100	1500	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
Web temperature after wire section	C	20	80	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83	42.83
Steam box steam	t/h	0	10	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5
Pressmb drying effective length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Prepressmb drying effective length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ref dryness before steam box	%	0	60	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
Dryer													
Tappi drying rate	kgH20/m^2h	0	35	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Impingement effective drying length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Calender													
mb finishing calender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Soft finishing calender nips	pcs	0	10	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Pressmb precalender nips	pcs	0	10	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Hard finishing calender nips	pcs	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Parameter	Unit	Min	Max	1	2	3	4	5	6	7	8	9	10
FixedInvest, OptiInvest													
General													
Product moisture after dryer section	%	2	10	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
High bulk product	on/off	0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Web width	m	5	15	8.marras	8.marras	8.marras	8.marras	8.marras	8.marras	8.marras	8.marras	8.marras	8.marras
Ref production speed	m/min	300	2000	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0
Ref total steam consumption without prepressmb, sb, fs, pressmb, dryer	t/h	0	40	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Production speed	m/min	300	2000	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0	584.0
Ref total gas consumption	kW	0	6000	1800.0	1800.0	1800.0	1800.0	1800.0	1800.0	1800.0	1800.0	1800.0	1800.0
Product basis weight	g/m2	45	350	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0
Ref total electricity consumption without prepressmb, fs, pressmb, imp, dryer, cal	kW	0	30000	15000.0	15000.0	15000.0	15000.0	15000.0	15000.0	15000.0	15000.0	15000.0	15000.0
Rate of interest	%	0	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Efficiency													
Unplanned ref annual shutdown time	h	0	1000	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0
Maximum available annual operating time	h	0	8760	8640.0	8640.0	8640.0	8640.0	8640.0	8640.0	8640.0	8640.0	8640.0	8640.0
Planned ref annual shutdown time	h	0	1000	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0
Production line total broke	%	0	50	7,5	7,5	7,5	7,5	7,5	7,5	7,5	7,5	7,5	7,5
Annual line break time at ref values	h	0	500	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Costs													
Wages price	MEUR/a	0	20	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Ref maintenance and wearing parts price without prepressmb, fs, pressmb, imp, dryer,	MEUR/a	0	10	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Other fixed price	MEUR/a	0	10	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Prices													
Filler, coat, size price	EUR/t	0	1000	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0	46.0
Pulp price	EUR/t	0	1000	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
A quality product market price at speed below vq	EUR/t	0	1000	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0	850.0
Product transportation price	EUR/t	0	100	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Product comission fee price	EUR/t	0	100	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Packaging material	EUR/t	0	1000	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
B quality product market price at speed above vq	EUR/t	0	1000	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0	800.0
Chemical price	EUR/t	0	1000	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Quality change speed	m/min	1200	2000	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0	1500.0
Other operating material	EUR/t	0	1000	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Water price fresh and effluent	EUR/t	0	1000	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
Energy prices													
Steam ton price	EUR/t	0	100	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
Gas price	EUR/MWh	0	100	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Electricity price	EUR/MWh	0	100	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0	55.0
Back-pressure turbine electricity production variable costs	EUR/MWh	0	1000	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Press													
Pressmb drying effective length	m	0	120	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Prepressmb drying effective length	m	0	20	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Ref dryness after press concept at design nip loads without sb, fs, pressmb	%	0	70	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0	53.0
Ref dryness before steam box	%	0	60	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Felt steamer steam	t/h	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Last press nip load	kN/m	500	1500	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
Steam box steam	t/h	0	10	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5	4,5
Dryer													
Impingement effective drying length	m	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Tappi drying rate	kgH20/m^2h	0	40	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Calender													
Soft finishing calender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pressmb precalender nips	pcs	0	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
mb finishing calender nips	pcs	0	10	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Hard finishing calender nips	pcs	0	20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Investment													
Investment residual value after inspection period	MEUR	0	100	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0
Dryer section machine hall investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Felt steamer investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Soft finishing calender investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
mb finishing calender investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Investment shutdown	h	0	1000	672.0	672.0	672.0	672.0	672.0	672.0	672.0	672.0	672.0	672.0
Prepressmb investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Hard finishing calender investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dryer section investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Impingement dryer investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pressmb precalender investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pressmb investment		0	1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
PCC production investment		0	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ref total investment costs without prepressmb, fs, pressmb, imp, dryer, cal, pcc plant	MEUR	0	300	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0	160.0

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The classical competitive firm is continuously searching for new ways to maximise profit. For this purpose there exist several methods to identify sources of losses and to calculate profitability or productivity of a production unit. However, the existing methods do not provide adequate information of how to calculate the profit potential related to changes in technology and process parameters.

This study applies a constructive research approach to develop a novel profit potential calculation method. The theoretical framework is the profit function, which is further developed to form the web profit model.

The findings show that the created profit potential method can be applied to web process profit potential analysis. Based on the profit potentials found it can be claimed that this novel method brings out significant potential to improve the profitability of the web processes.

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