LUT UNIVERSITY
LUT School of Energy Systems
LUT Mechanical Engineering

Mikko Ryhänen

COMPARISON OF MANUFACTURING CONCEPTS FOR AUTOMATIZATION OF IMPELLER BALANCING

17.05.2019

Examiners: Professor Harri Eskelinen

M. Sc. (Tech.) Petri Taipale

TIIVISTELMÄ

LUT Yliopisto
LUT Energiajärjestelmät
LUT Kone

Mikko Ryhänen

Comparison of manufacturing concepts for automatization of impeller balancing

Diplomityö

2019

103 sivua, 28 kuvaa, 36 taulukkoa, 9 kaavaa ja 4 liitettä

Tarkastajat: Professori Harri Eskelinen
DI Petri Taipale

Hakusanat: jäykän roottorin tasapainotus, epätasapaino, automatisointi, tuotantosolun suunnittelu, tuotannon optimointi, kehittynyt tuotantoteknologia, AMT, arvoanalyysi, riskianalyysi, juoksupyörä

Tämän tutkimuksen päätavoitteena oli tunnistaa eniten arvoa lisäävät valmistuskonseptit juoksupyörän tasapainotuksen automatisoinnille kohdeyrityksessä ja kehittää asianmukainen arviointimenetelmä investoinnin perustelemiselle. Kolmea valmistuskonseptia vertailtiin keskenään; konsepti 1 koostuen epätasapainon mittaamisesta integroituna automaattiseen epätasapainon korjaukseen, konsepti 2 koostuen erillisestä epätasapainon mittaamisesta ja automaattisesta epätasapainon korjauksesta ja konsepti 3 koostuen erillisestä epätasapainon mittaamisesta, automaattisesta epätasapainon korjauksesta sekä automaattisesta juoksupyörän halkaisijan sorvauksesta. Vertailu perustui konseptien arvojen ja suhteellisten riskitasojen suhteuttamiseen.

Tiedonkeruumenetelmät muodostivat lähdetriangulaation tieteellisen kirjallisuuden, kohdeyrityksen sisäisten lähteiden ja kaupallisten lähteiden välille. Valmistuskonseptien analysointi koostui arvoanalyysistä, riskianalyysistä ja vertailusta tasapainotuksen nykytilaan kohdeyrityksessä. Automaattisen epätasapainon korjauksen toimivuus varmistettin lopuksi käytännön testillä.

Investointisuositus annettiin valmistuskonseptille 3 perustuen konseptien arvoihin suhteutettuna konseptien suhteellisiin riskitasoihin. Konseptin 3 merkittävimmät hyödyt koostuivat tuotannollisesta joustavuudesta, mahdollisuuksista laajentaa toiminnallisuutta, toiminnallisesta varmuudesta sekä saavutetusta automaation tasosta, joka eliminoi nykyisen tasapainotuskonseptin haittapuolia. Konseptin 3 haittapuolet koostuivat valmistuskonseptin monimutkaisuudesta, riskeistä liittyen koneiden vioittumiseen, käytettävyyteen ja käyttöönottoon sekä suhteellisen korkeisiin investointikustannuksiin korottaen tuotantosolun käyttöastevaatimuksia. Juoksupyörien tasapainotuksen arvoa voidaan lisätä merkittävästi automatisoinnilla, mutta yksityiskohtainen suunnitteluvaihe on tärkeä toiminnan optimoinnin, riskienhallinnan sekä käyttöönoton suunnittelun kannalta.

ABSTRACT

Lappeenranta University of Technology
LUT School of Energy Systems
LUT Mechanical Engineering

Mikko Ryhänen

Comparison of manufacturing concepts for automatization of impeller balancing

Master's thesis

2019

103 pages, 28 figures, 36 tables, 9 equations and 4 appendices

Examiners: Professor Harri Eskelinen
M. Sc. (Tech.) Petri Taipale

Keywords: rigid rotor balancing, unbalance, automatization, production cell design, production optimization, advanced manufacturing technology, AMT, value analysis, risk analysis, impeller

The main purpose of this study is to identify and select the most valuable manufacturing concept for automatization of impeller balancing at target company and develop a proper evaluation system to justify the investment. Three manufacturing concepts were compared; concept 1 including unbalance measuring integrated with automatic correction in same station, concept 2 including separate unbalance measuring and automatic unbalance correction stations and concept 3 including separate unbalance measuring, automatic correction and automatic impeller diameter trimming stations. The comparison was based on the relative values and risk levels of the three concepts.

Data collection methods formed a source triangulation of scientific literature, target company's internal sources and commercial sources. Data analysis of manufacturing concepts consisted of value analysis, risk analysis and comparison to current status of balancing at target company. Ultimately, functionality of automatic unbalance correction method was verified with a practical test.

The recommendation to invest in manufacturing concept 3 was given based on value adjusted to relative risk level. Key benefits of concept 3 consisted of production flexibility, options to extend functionality, operational reliability and achieved level of automation eliminating disadvantages of existing balancing concept. Disadvantages of concept 3 consisted of complexity of manufacturing concept, risks related to machine malfunction, usability and implementation and relatively high investment costs requiring increased utilization rate. In conclusion, significant value can be added to impeller balancing with automatization, but a detailed design phase is essential for ensuring optimized operation, conducting proper risk management and planning successful implementation.

ALKUSANAT

Tämä diplomityö on todistus siitä, että diplomityön, kolmen muun työtehtävän, muutaman opintojakson ja lähestulkoon ammattimaisuutta hipovan jalkapalloharrastuksen yhdistäminen puolen vuoden ajanjaksolle ei riko miestä. Vähän tuli ehkä liioiteltua jonkin asian suhteen, mutta vauhti on ollut päällä joka tapauksessa.

Tästä rytäkästä selvittyäni, haluan ensin kiittää Harri ”Harza” Eskelistä ammattimaisesta diplomityöni ohjaamisesta sekä opetuksesta koko opintojeni ajalta. Harzaa haluan erityisesti kiittää analyyttisen lähestymistavan iskostamisesta takaraivooni. Haluan jakaa erityiskiitokset myös Tommi Ratialle kannustavasta diplomityön ohjaamisesta. Kaiken syväluotaavan analyysin ohella Tommi varmisti, että käytännöllisyys ja työelämän realiteetitkin tulivat huomioitua. Kiitokset myös Petri Taipaleelle työni tarkastamisesta kohdeyrityksen puolesta.

Isot kiitokset Jukka Rantaselle siitä, että olen opintojeni aikana saanut hoitaa vastuullisia ja mielenkiintoisia työtehtäviä. Jukka piti huolen siitä, että rankkojen kevätlukukausien jälkeen mieltä ei koskaan tarvinnut stressata kesän lomasuunnitelmilla.

Viimeiset kiitokset haluan jakaa vielä Jukka Tanille, joka varmisti että diplomityönkin jälkeen pohdittavaa tulee riittämään ja että jalkapallosta ei onneksi tule ainoata elinkeinoani.

Mikko Ryhänen
Etelä-Carolinassa, 17.05.2019

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

d_{imp}	impeller diameter [mm]
F	unbalance force [N]
G	center of gravity
G_s	selected balance quality grade
L	distance between planes A and B
L_A	distance between plane of center of mass and plane A
L_B	distance between plane of center of mass and plane B
m	mass [kg]
n	service speed [rpm]
t	correction width [mm]
t_{max}	maximum correction width by eccentric turning [mm]
t_1	original hub disk thickness [mm]
t_2	hub disk thickness after correction [mm]
U	unbalance [gmm]
$U_{initial}$	initial unbalance [gmm]
U_{per}	permissible residual unbalance [gmm]
U_{perA}	permissible residual unbalance in tolerance plane A [gmm]
U_{perB}	permissible residual unbalance in tolerance plane B [gmm]
U_{per1}	permissible residual unbalance in correction plane 1 [gmm]
U_{per2}	permissible residual unbalance in correction plane 2 [gmm]
U_{res}	residual unbalance [gmm]
W	weight factor
τ	angle error between rotational axis and principal axis of inertia [rad]
ε	eccentricity [mm]
Ω	angular velocity of rotor [rad/s]

AI	artificial intelligence
AMT	advanced manufacturing technology
CAM	computer-aided manufacturing
CM	center of mass

CNC	computer numerical control
GA	geometric average
gmm	gram millimeters
MADM	multi-attribute decision-making
NC	numerically controlled
OEM	original equipment manufacturer
RC	relative cost
RPC	risk priority class
RPN	risk priority number
rpm	revolutions per minute

1 INTRODUCTION

Excessive vibration during operation of centrifugal pump can cause severe damage to its structure and result in malfunction of the pumping unit. This may lead to costly downtime in a process where fluids or slurries are moved by the pump. Unbalance in pump's impeller transmits vibration to the whole pumping system and its surroundings. This also means that surrounding machinery and instruments may be damaged if vibration level exceeds allowable limits (Matsushita, Tanaka & Kanki et. al. 2017, p. 108; Tiwari 2010, p. 767). It is stated in several studies that unbalance is the most typical or major source for adverse vibration in rotating systems and common issue in operation of rotating machinery (Matsushita et. al. 2017, p. 105; Tiwari 2010, p. 766; Kumar, Diwakar & Satynarayana 2012, p. 3415). Additionally, unbalanced impeller decreases flow rate of the pump and causes local pressure drops that lead to turbulent flow and possibly cavitation (Taneja 2013, p. 57). Local high pressures caused by cavitation may exceed strength limitations of pump's hydraulic components and lead to cavitation erosion (Centrifugal Pump Handbook 2010, p. 14). Thus, impeller balancing is an inevitable manufacturing step in centrifugal pump manufacturing.

Due to manufacturing errors, unbalance occurs at some level in every practical rotating machinery. Impellers of target company are cast components and it is commonly known that dimensional and structural errors are typical when casting is used as a manufacturing method. Therefore, the importance of balancing for impellers is emphasized. Balancing refers to a process where rotor unbalance is assured to meet the specified limits given (SFS-ISO 21940-2 2017, p. 10). Main stages of balancing are measuring unbalance and unbalance correction. Correction refers to a process where mass distribution of rotor is adjusted to reduce rotor unbalance to meet the given tolerance grade (SFS-ISO 21940-2 2017, p. 11). Rotors can be categorized by their mechanical behavior. Impeller is categorized as a rigid rotor, so data collection phase focuses only in rigid rotor unbalance and balancing.

1.1 Research problem

This Master's thesis has been commissioned by a company that manufactures process pumps as one of their main products. From now on, the company is referred to as a target company in this study. Currently, impeller balancing in target company's factory requires manual work, the most challenging manual work phase being unbalance correction by removing material with angle grinder. Employee is vulnerable to bad work ergonomics in correction where material is typically removed with angle grinder. Grinding creates hazardous metallic dust in the near atmosphere and employees must wear protective clothes, masks and ventilation filters when grinding. Structural materials of impellers are relatively hard, which is why a certain level of physical endurance is required from employee to be able to grind efficiently, specifically when daily workload in balancing cell is high. As quality of impeller is essential for hydraulic performance of centrifugal pump, following quality standards and internal guidelines is required in balancing. Precision in grinding is required from the employee due to complex designs of impellers and quality requirements set for material removal. In some impeller models, the material removal areas are narrow in comparison to grinding wheel's diameter, which makes to process even more challenging. Material cannot be removed while impeller is fixed to unbalance measuring machine also known as balancing machine, therefore impellers must be moved with manual heist to adjacent correction table. In correction, the amount of material removed must be evaluated visually by employee and then impeller is moved again to balancing machine to check how much material was removed by grinding. Impellers can weigh hundreds of kilograms, which is why extra cautiousness is required in material handling. If specified limitations for unbalance are not met, correction must be repeated. Occasionally, this measuring-correction cycle must be repeated several times which leads to increased impeller lead times. Therefore, increasing automation in impeller balancing could lead to significant benefits. Figure 1 illustrates typical impeller design of target company.

Figure 1. Typical impeller design of a centrifugal pump manufactured by target company (SNS End Suction Single Stage Centrifugal Pumps 2017, p. 7).

As can be seen from figure 1, impeller design is complex and requires precision in manufacturing. In impeller balancing, places for possible correction are considered carefully to retain designed hydraulic performance and reliability of impeller. At target company, correction is mainly done by removing material manually with angle grinder. Thus, there is a risk of human error that may lead to unnecessary drop in impeller's quality. Although unbalance is measured after correction and meets specified limitations, there is a possibility of accidentally creating adverse shapes to impeller surface that may affect pump's hydraulic performance and reliability. In conclusion, strict quality demands, challenging working conditions, complexity and variety of impellers in balancing form the research problem of this study.

1.2 Goal of the study and research questions

The main purpose of this study is to identify and select the most valuable manufacturing concept for automatization of impeller balancing at target company and develop a proper evaluation system to justify the investment. Justification consists of evaluation, selection and comparison to existing balancing concept. Automation can add significant value to manufacturing, while it may also create new risks to be managed in production. Therefore, different concepts are evaluated by combining value analysis and risk analysis to form a relation of value and risk for each manufacturing concept examined. Ultimately, the concept providing the best relation of value and risk level is recommended for target company and implementation plan is presented. Main research questions for the study are formed as:

- How the value of impeller balancing cell can be increased?
- What kind of manufacturing concepts could be utilized in impeller balancing cell to add value?
- Which one of the examined manufacturing concepts adds the most value for target company?

1.3 Research methods and scope

Data collection is based on source triangulation of scientific literature, target company's internal sources and commercial sources. Scientific literature is studied from scientific articles, standards and educational material. Target company's internal sources consist of work instructions, quality plans and applied standards. Additionally, semi-structured interviews are conducted with employees working in balancing cell. Commercial sources consist of www-sources, product datasheets, preliminary quotations and discussions with suppliers and original equipment manufacturers (OEM).

Data analyzing is based on value analysis, risk analysis and comparison to current status of balancing at target company. Value analysis evaluates essential properties of manufacturing concepts and relates them to relative investment costs to obtain values for each concept. Risk analysis identifies the most significant risks related to automatization of impeller balancing and determines relative risk levels based on probabilities and severities of risks for each concept. Ultimately, values obtained from value analysis are adjusted to relative risk levels.

Finally, a practical test is conducted to verify functionality of examined automatic unbalance correction, which is the most challenging phase in terms of automatization. Practical test aims also to recognize issues that should be considered to ensure operational reliability of automatic correction. Scope of the research was set in cooperation with target company as follows:

- Impellers: process pump impeller sizes 1–7.
- Unbalance tolerances: balance quality grades G 6.3, G 2.5 and G 1.0 according to SFS-ISO 21940-11.
- Balancing: single-plane and two-plane balancing for rigid rotors.
- Unbalance correction: methods based on material removal.

Impellers selected belong to the most popular product category of target company. Unbalance tolerances of target company follow balance quality grades G in SFS-ISO 21940-11, which is why no other unbalance tolerances are examined. Balancing is limited to single-plane and two-plane balancing for rigid rotors, single-plane balancing being the focus in terms of automation. Correction is limited to methods based on material removal as per internal guidelines of target company.

2 RIGID ROTOR BALANCING

The purpose of this chapter is to achieve a comprehensive understanding of rigid rotor balancing principles, which is a part of data collection phase that aims to identify how the value of impeller balancing is determined and what are the critical risks related to automation of the process. The following key topics are covered regarding balancing:

- Unbalance in rigid rotor
- Balancing of rigid rotor
- Unbalance tolerances for rigid rotors

Topics above play a vital role in understanding and identifying the key evaluation criteria of selecting new manufacturing concepts for impeller balancing at target company. Without understanding the fundamentals of factors affecting balancing, there is a significant risk of selecting unsuitable techniques and processes.

2.1 Unbalance in rigid rotor

Rotors can be classified as rigid or flexible rotors, which possess different mechanical behaviors. Impellers of centrifugal pumps at target company are classified as rigid. When talking about rotors with rigid behavior, flexure caused by rotor's unbalance can be neglected given that unbalance does not exceed tolerances at any rotational speed up to maximum service speed (SFS-ISO 21940-2 2017, p. 5). More specifically, rotors operating 30 % or more below of their resonance speed are defined as rigid (Ruehs 2013, p. 1).

Rotor is in unbalance when its mass is unevenly distributed across the part. Some amount of unbalance occurs in rotor always due to various reasons such as manufacturing errors or material in-homogeneity (Tiwari 2010, p. 766). Unbalance (U) can be expressed in gram millimeters (gmm) as designated by equation 1: (Matsushita et al. 2017, p. 105)

$$U = m \cdot \varepsilon \quad \text{[gmm]} \tag{1}$$

In equation 1, U = unbalance, m = mass of rotor and ε = eccentricity. The radial distance between rotor's center of gravity (G) and geometric center also known as centroid (S), is called eccentricity (ε). When rotor is rotating, centrifugal force caused by unbalance can be expressed as unbalance force (F) by following equation: (Matsushita et al. 2017, p. 105)

$$F = U \cdot \Omega^2 \quad [N] \tag{2}$$

In equation 2, F = unbalance force, U = unbalance and Ω = angular velocity of rotor. Unbalance in rotor can be classified as static, couple or dynamic unbalance. (Matsushita et al. 2017, p. 105-107.)

2.1.1 Static unbalance

Static unbalance occurs when there is parallel displacement between principal axis of inertia and rotational axis that is also referred to as shaft axis. As SFS-ISO 21940-2 defines, principal axis of inertia is defined as "one of three mutually perpendicular axes where products of inertia in a solid body are zero" (SFS-ISO 21940-2 2017, p. 5). In balancing, the principal axis of inertia is referred to as the axis most nearly coincident with the rotational axis. (SFS-ISO 21940-2 2017, p. 5, 9.) Figure 2 presents conditions of static unbalance.

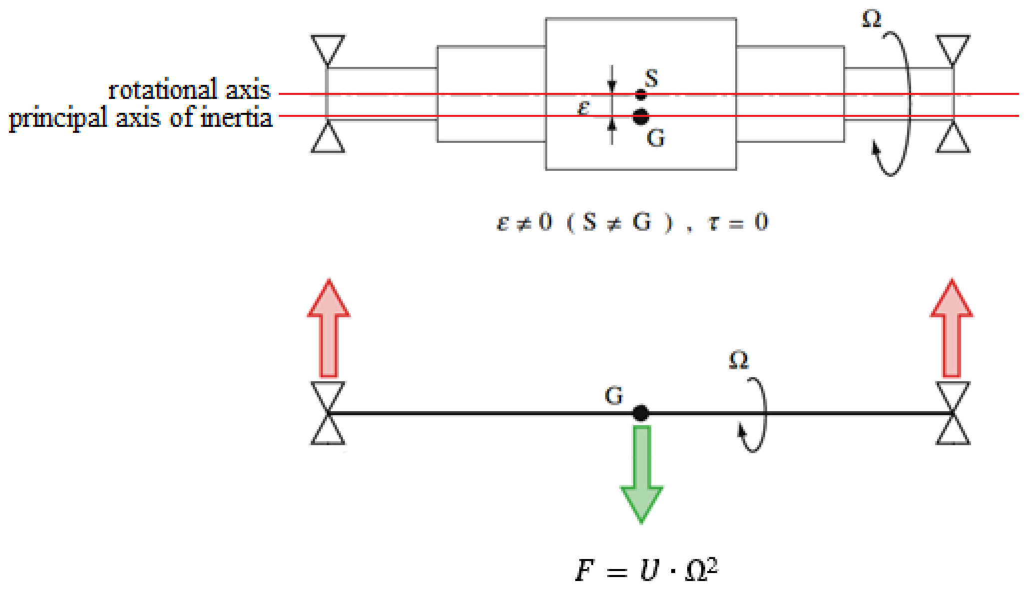


Figure 2. Conditions of static unbalance in rigid rotor and reaction forces transmitted to bearings. τ = angle error between rotational axis and principal axis of inertia. (paraphrasing Matsushita et al. 2017, p. 106.)

Reaction forces to bearings caused by static unbalance in figure 2 are equal. When thinking of unbalanced rotor in operation, directions of unbalance force and reaction forces vary continuously according to rotation of rotor. (Matsushita et al. 2017, p. 105-106.)

Theoretically, static unbalance can be detected without rotating the rotor. If rotor is placed on bearings with close to zero friction, it will eventually settle on a position where unbalance is headed downwards (Matsushita et al. 2017, p. 105-106). Clearly, detecting static unbalance with almost frictionless bearings without rotating the rotor is not practical. It requires multiple trials and may still give uncertain and inaccurate results. Therefore, practical static balancing is mostly done by rotating the rotor. (SFS-ISO 21940-11 2017, p. 8.)

2.1.2 Couple unbalance

Couple unbalance occurs when center of gravity G is coincident with centroid S, but there exists angular misalignment between principal axis of inertia and rotational axis. This causes two equal unbalance forces to opposite sides of the rotor with 180 degrees difference in direction of the force, which causes bending moment to rotor. (Matsushita et al. 2017, p. 108; SFS-ISO 21940-2 2017, p. 9) Figure 3 illustrates conditions of couple unbalance.

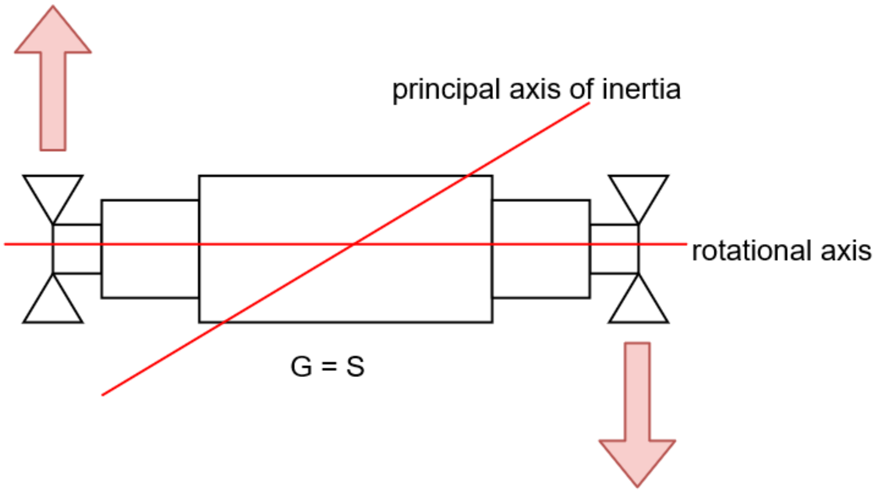


Figure 3. Conditions of couple unbalance in rigid rotor. (paraphrasing Matsushita et al. 2017, p. 108).

As figure 3 shows, G is equivalent to S but angular error between the axes creates unbalance forces.

2.1.3 Dynamic unbalance

Dynamic unbalance occurs when principal axis of inertia has any inclined and offset position related to rotational axis (SFS-ISO 21940-2 2017, p. 9). It is stated as the most common case of unbalance and it accounts for all the unbalance that exists in a rotor. (Kalmegh & Bhaskar 2012, p. 410). This means that it can be produced as a combination of static and couple unbalance (SFS-ISO 21940-2 2017, p. 9; Kalmegh & Bhaskar 2012, p. 410). Figure 4 illustrates conditions for dynamic unbalance.

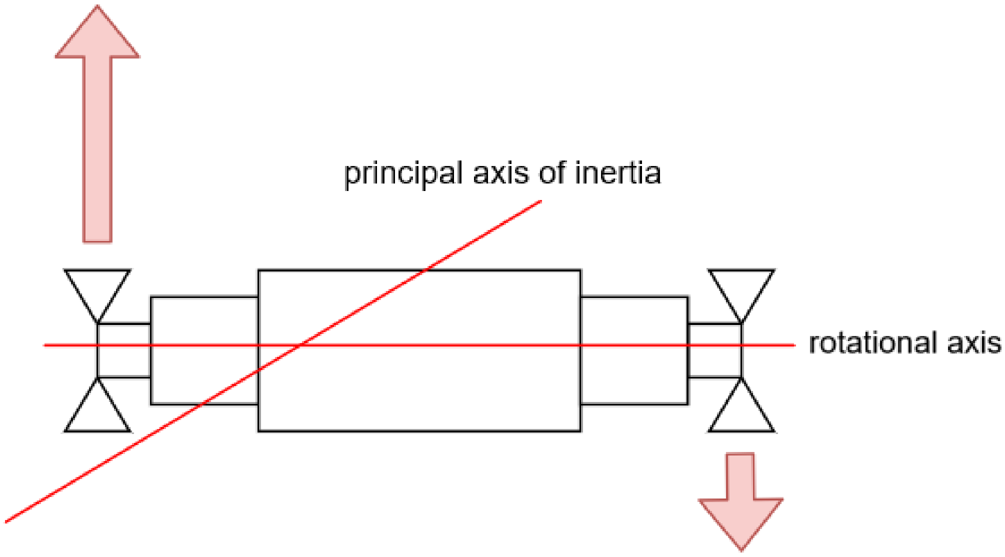


Figure 4. Conditions of dynamic unbalance in rotor (paraphrasing Matsushita et al. 2017, p. 106).

Reaction forces created by dynamic unbalance illustrated in figure 4 differ from each other. Dynamic unbalance can be expressed also as two static unbalances in different planes. For example, this kind of expression is required when allocating amount of unbalance to be removed from two correction planes. (Matshushita et al. 2017, p. 107; Kalmegh & Bhaskar 2012, p. 410.)

2.1.4 Adverse effects of unbalanced rotor in pumping system

As previously introduced, unbalance combined with centrifugal force during rotation causes unbalance force. When unbalanced impeller rotates inside the pump, unbalance force changes its direction continuously, which then leads to vibration in bearings and whole pumping system. This means that also surrounding machinery and instruments may be damaged if vibration level is high (Matsushita et al. 2017, p. 108; Tiwari 2010, p. 767).

Unbalance in impeller decreases flow rate of the pump and causes local pressure drops that lead to turbulent flow and in the worst case, cavitation (Taneja 2013, p. 57). Local high pressures caused by cavitation may exceed strength limitations of pump’s hydraulic components and lead to cavitation erosion (Centrifugal Pump Handbook 2010, p. 14).

If a rotating system, such as centrifugal pump, operates near its resonance speed, the affecting unbalance forces in rotor are significantly strengthened and exceptionally high stresses may be transmitted to supporting structures. Resonance speed, also known as critical speed, is defined as rotational speed at which resonance is excited in a rotating system (SFS-ISO 21940-2 2017, p. 5). Resonance may occur during pumps operation due to previously mentioned cavitation erosion. Cavitation erosion leads to loss of mass in pump impeller and thus it may change natural frequency and resonance speed of the rotating system close to pump's operating speed. As mass distribution of impeller is modified due to cavitation erosion, it creates unbalance forces to the system. (Adamkowski, Henke & Lewandowski 2016, p. 70-71.) While operating near resonance speed should be avoided, this also highlights the importance of balancing in case resonance speed is reached for some reason. (Heindel, Becker & Rinderknecht 2017, p. 339.)

2.2 Balancing of rigid rotor

Balancing is defined as a procedure of ensuring unbalance in rotor is in acceptable limits. If necessary, rotor’s mass distribution will be adjusted to reach the limit. (SFS-ISO 21940-2 2017, p. 8.) Mass distribution of rotor can be modified by removing, relocating or adding material. There exist several balancing methods for different kind of rotors and circumstances (Kalmegh & Bhaskar 2012, p. 410). The most common balancing method at target company is single-plane balancing, whereas two-plane balancing can be performed with certain limitations for impellers of process pumps (paraphrased from company internal sources). Other balancing methods are not utilized and so are not included in this study.

Measure uncertainties are given in gram millimeters for balancing machines. This means that for different impeller radiuses, there is a different amount of uncertainty in measured unbalance mass in grams. Therefore, impellers with smaller diameters require more accurate balancing machines. Measurement errors in balancing are specified in SFS-ISO 21940-14 standard.

According to Matshushita et al., there currently exists two types of commercial dynamic balancing machines for rigid rotors, which are hard-bearing and soft-bearing balancing machines. In hard-bearing machines calculating residual unbalance (U_{res}) is based on bearing reaction forces. In soft-bearing machines the bearings act like springs, and calculation is based on bearing vibrations. (Matsushita et al. 2017, p. 108-109.) U_{res} is defined as unbalance in rotor after balancing has been performed (SFS-ISO 21940-2 2017, p. 9). Due to the measuring principle of soft-bearing machines, they must always be calibrated when rotor type to be balanced is changed. This is because bearing vibrations are dependent not only on forces caused by unbalance, but also on rotor mass and mass distribution. Hard-bearing machines enable permanent calibration and there is generally no need for calibration when rotor type is changed. Hard-bearing principle enables also wider range in rotor weight and amount of unbalance to be accurately measured. These are some of the reasons why hard-bearing machines are rapidly becoming more popular than soft-bearing machines. (Dynamic balancing machines, p. 2-3.)

Balancing rigid rotors at lower speeds gives advantages in comparison to balancing at higher speeds. Lower balancing speed consumes less energy, reduces wear of rotating parts and may improve lead time of balancing with faster acceleration and deceleration. There are no requirements that balancing speed should match the operating speed of rigid rotor in its application. However, some balancing machines may be able to measure smaller unbalance at lower speeds than other balancing machines. (Basic theory of dynamic balancing, p. 3-4.) Effect of balancing speed to measurement results was also researched but any articles directly describing the effects were not found during this study. This topic should be studied more to be able to make correct conclusions about suitable balancing speeds.

2.2.1 Single-plane and two-plane balancing

Depending on impeller model, single-plane (in some sources referred as static) or two-plane (in some sources referred as dynamic) balancing is performed at target company. Difference between these balancing procedures is the number of planes in which measuring unbalance and possible corrections are made. Dynamic unbalance can be detected only by two-plane balancing, while static unbalance can be detected by both balancing procedures. (SFS-ISO 21940-2 2017, p. 11; Tiwari 2010, p. 768.)

In two-plane balancing, permissible residual unbalance (U_{per}) is allocated to two tolerance planes instead of one. Therefore, correction happens also in two correction planes, which may differ from tolerance planes. Tolerance plane is defined as a plane where unbalance tolerance is specified. (SFS-ISO 21940-2 2017, p. 11; SFS-ISO 21940-11 2017, p. 15.) In practical applications, correction planes are determined depending on factors such as rotor design, rotor shape and acceptable areas for removing, adding or relocating material (SFS-ISO 21940-11 2017, p. 8; Tiwari 2010, p. 769). Figure 5 illustrates allocation of U_{per} in two-plane balancing of inboard rotor. Inboard means that rotor body is placed between bearings (A and B in figure) instead of hanging outside.

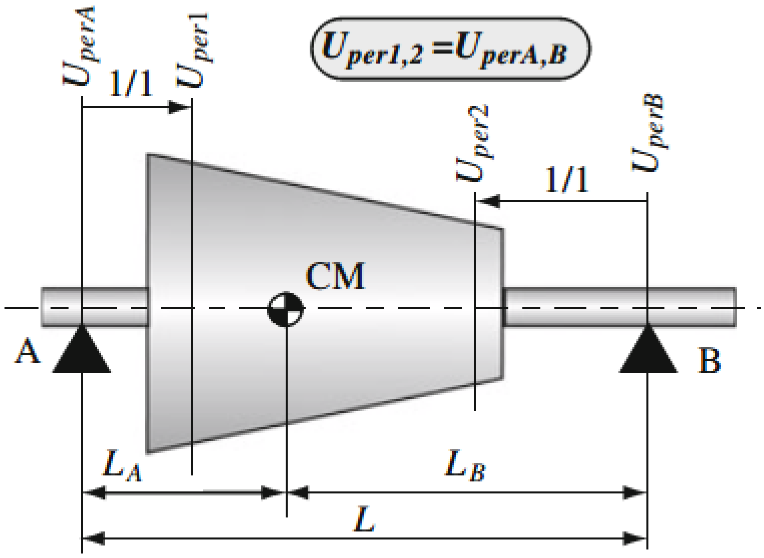


Figure 5. U_{per} is divided into two tolerance planes in two-plane balancing. Tolerance planes are set in line with bearing planes and correction planes are set to both sides of rotor body. (paraphrased from Matsushita et al. 2017, p. 110.)

In figure 5, CM = center of mass, U_{perA} = permissible residual unbalance in tolerance plane A, U_{perB} = permissible residual unbalance in tolerance plane B, U_{per1} = permissible residual unbalance in correction plane 1, U_{per2} = permissible residual unbalance in correction plane 2, L = distance between planes A and B, L_A = distance between plane of center of mass and plane A and L_B = distance between plane of center of mass and plane B (Matsushita et al. 2017, p. 110). U_{per} is calculated for both tolerance planes as in equations 3 and 4: (Matsushita et al. 2017, p. 110; SFS-ISO 21940-11 2017, p. 15)

$$U_{perA} = U_{per}L_B/L \qquad \text{[gmm]} \qquad (3)$$

$$U_{perB} = U_{per} L_A / L \qquad \text{[gmm]} \qquad (4)$$

In equations 3 and 4, U_{perA} = permissible residual unbalance in tolerance plane A, U_{perB} = permissible residual unbalance in tolerance plane B, L = distance between planes A and B, L_A = distance between plane of center of mass and plane A and L_B = distance between plane of center of mass and plane B (Matsushita et al. 2017, p. 110).

2.3 Unbalance tolerances for rigid rotors

Utilizing balance quality grades G is a common way to evaluate whether unbalance is in tolerance for a certain application. Balance quality grades for rigid rotors were defined in standard SFS-ISO 1940-1 until 2017, when it was replaced by standard SFS-ISO 21940-11 currently in use. Additionally, SFS-ISO 21940-2 identifies terms and definitions used in SFS-ISO 21940-11. SFS-ISO 21940-11 defines five different methods for determining the permissible residual unbalances for rigid rotors (SFS-ISO 21940-11, p. 10-11). Of these methods, applying balance quality grades G is used at target company, hence it is the only method examined in this research. With balance quality grades G, U_{per} is calculated as in equation 5 (SFS-ISO 21940-11 2017, p. 14, 22):

$$U_{per} = 9549\ G_s m / n \qquad \text{[gmm]} \qquad (5)$$

In equation 5, U_{per} = permissible residual unbalance (gmm), G_s = selected balance quality grade (mm/s), m = rotor mass (kg) and n = service speed (rpm) (SFS-ISO 21940-11 2017, p. 14). As equation 5 illustrates, the higher the service speed of a pump is, the lower is permissible residual unbalance for impeller. Therefore, pump's operating conditions are relative to U_{per} of its impeller.

2.3.1 Applied balance quality grades G for impellers

SFS-ISO 21940-11 provides guidance in balance quality grades for rigid rotors. According to standard, general guidance for pumps' balance quality grade is G 6.3, which allows magnitude of 6,3 mm/s. (SFS-ISO 21940-11 2017, p. 12.) In addition, balance quality grades G 2.5 or G 1.0 are occasionally used at target company, depending on pump type, end application and customer requirements.

As impeller is eventually attached to its shaft, it forms a rotating assembly of two individual parts. For the most efficient and reliable way to ensure that residual unbalance does not exceed limitations, impeller should be assembled to its shaft and balancing should be performed to this rotating assembly. This way assembly errors would also be considered in unbalance measurement. If balancing is done individually for shaft and impeller, aspects such as the effect of combined errors or effect of connecting elements between the parts should be considered. For example, if assembly errors cannot be ignored in terms of balancing, individual parts should be balanced to a lower residual unbalance than the complete rotating assembly. (SFS-ISO 21940-11 2017, p. 18.) This could mean that stricter balance quality grades G would be applied for individual parts in such cases.

2.4 Summary of rigid rotor balancing

Unbalance of rigid rotor can be categorized as static, couple or dynamic unbalance, of which dynamic unbalance accounts for all unbalances existing in rigid rotor. Static unbalance can be detected by single-plane balancing, but dynamic unbalance requires two-plane balancing. For balancing, hard-bearing machines are rapidly overtaking soft-bearing machines in the market. Excessive vibration causes serious issues in operation of a centrifugal pump and a common source of adverse vibration is unbalance of a rotor, in this case shaft and impeller. Issues may occur in pump’s operational performance as well as reliability. Therefore, unbalance tolerances such as balance quality grades G determined in SFS-ISO 21940-11 should always be applied for impellers and mass distribution adjusted in case of excessive unbalance. Balance quality grade G 6.3 was stated as recommendation for pump impellers according to SFS-ISO 21940-11.

3 RESEARCH METHODS

This study is divided in three main research phases that are data collection, data analyzing and verification. Structure of the study is illustrated in figure 6.

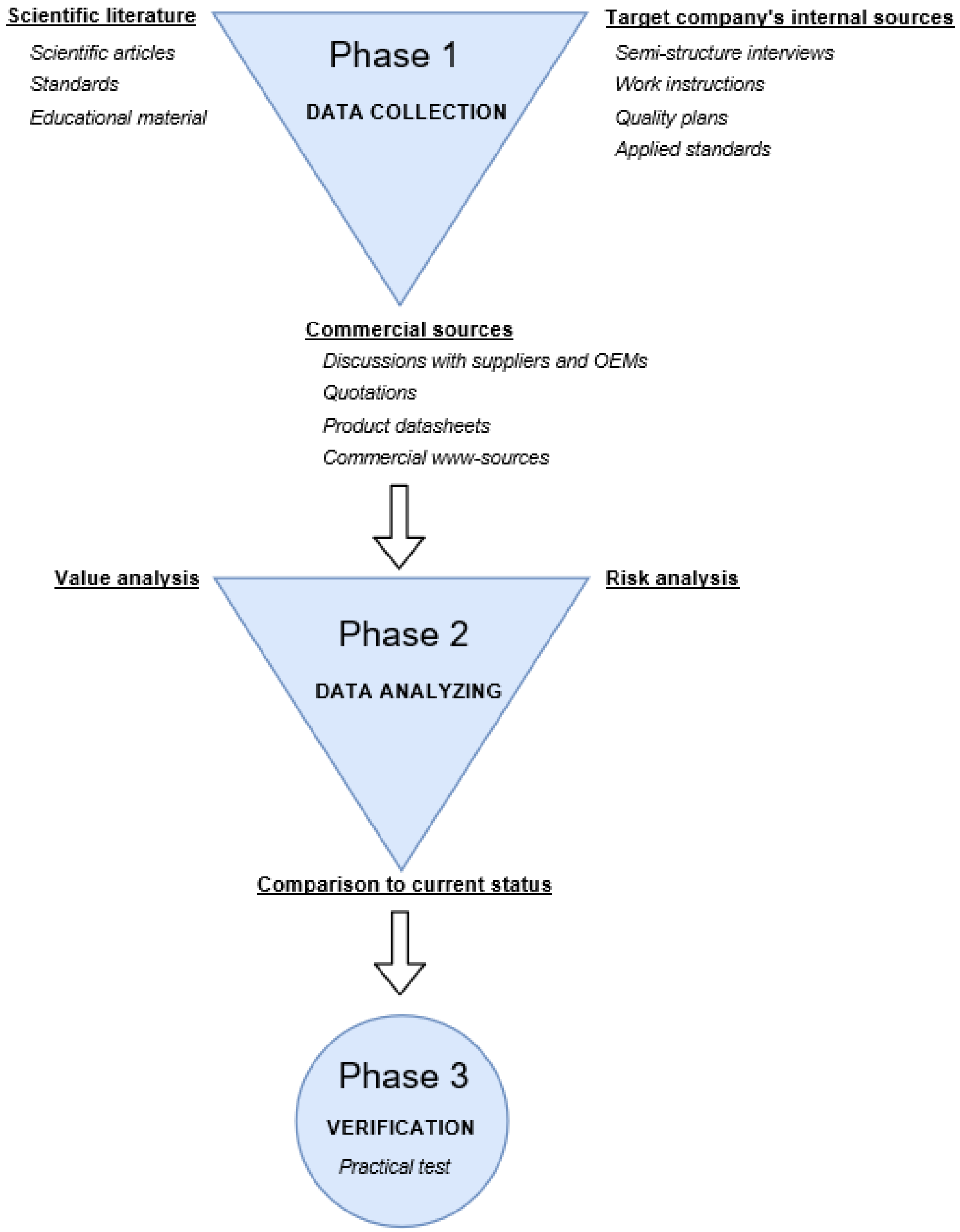


Figure 6. Illustration of research stages and methods utilized in this study.

As shown in figure 6, data collection forms a source triangulation of scientific literature, target company's internal sources and commercial sources. Data is then analyzed with value analysis, risk analysis and comparison to current status of balancing at target company. These data analyzing methods aim to identify the most valuable manufacturing concept and to form a comprehensive justification process for investing in new manufacturing concept. Finally, functionality of automatic unbalance correction is verified by practical test. Verification focuses on correction, as it is the most demanding and limiting factor in terms of automatization.

3.1 Data collection to form basis for value analysis and risk analysis

The purpose of data collection phase is to achieve comprehensive understanding of value adding elements in balancing and to identify the most significant risks existing in automatization of impeller balancing. Additionally, the goal is to identify and examine potential manufacturing concepts for automatization.

Discussions with suppliers and OEM’s, product datasheets, commercial www-sources and preliminary quotations are examined to understand and identify commercial possibilities to match requirements of balancing in automatization of the process.

3.1.1 Research of scientific literature

Sources of scientific literature research consist of standards, scientific articles and educational material. Topics examined consist of unbalance in rigid rotor, rotor balancing methods and existing balancing tolerances. Unbalance in a rotor is defined and different types of unbalances are examined to understand the basics. Importance of balancing is recognized by examining the negative effects of rotor unbalance on a pumping system. Rotor balancing is examined from the viewpoint of study scope and relevant balance quality grades according to SFS-ISO 21940-11 are studied.

3.1.2 Research of target company’s internal sources

Target company’s internal work instructions, quality plans and applied standards are examined and semi-structured interviews of balancing employees are conducted to gather detailed information from balancing process performed specifically at target company. Semi-structured interviews aim also to identify the most challenging and unpleasant work phases during balancing and to find the key phases where value could be added. Interviews of each employee are based on the questions presented in appendix 1. Additionally, two randomly selected impellers belonging to study scope were balanced at target company’s environment by the researcher to further understand details of the process.

3.1.3 Research of commercial sources

First, pre-comparison of various commercial concept categories to add value to balancing was performed between three categories:

- Category 1: small size improvements without automation
- Category 2: medium size improvements by semi-automatic solutions
- Category 3: large size improvements aiming for full automatization

Pre-comparison aims to verify that focusing on manufacturing concepts that aim to maximize automation is the most effective choice to add value to balancing cell. This kind of pre-comparison was required, as semi-structured interviews indicated that there exist also other ways to add value than maximizing the level of automation (Semi-structured interviews 2019). Ultimately, it was verified that category 3 would be the most efficient way of adding value to balancing. Therefore, research of commercial sources focused on category 3.

Commercial www-sources, product datasheets, preliminary quotations and discussions with suppliers and OEM’s formed the basis in research of commercial sources. Eventually, three most promising manufacturing concepts with related suppliers and OEM’s were examined and compared to each other. A decision to include three concepts was made so that reliability of comparison would not suffer due to complexity of research problem and amount of different manufacturing concepts.

3.2 Data analysis to identify and select the most valuable manufacturing concept

Automatization of impeller balancing requires implementation of advanced manufacturing technology (AMT). It is stated that multi-attribute decision-making (MADM) techniques should be utilized to achieve a proper evaluation and selection process for AMTs (Goyal & Grover 2012, p. 262). Evaluation and selection process of manufacturing concepts is based on combining results of value analysis with results of risk analysis to obtain relation of value and relative risk levels for each concept. This MADM system is built into Microsoft Excel with adjustable parameters so that evaluation and selection process can be adjusted in case needed after study. Finally, comparison to current state of impeller balancing at target company is performed to complete justification for recommended manufacturing concept. Any standards directly considering automatization of impeller balancing were not found during this study.

3.2.1 Value analysis of manufacturing concepts

The main purpose of value analysis is to increase value of an analyzed object. Value is defined as the relation of function and cost as follows: (Meskanen 2017, p. 5-6.)

$$Value = \frac{function}{cost} \tag{6}$$

In equation 6, function is equal to properties of the analyzed object. Therefore, value can be added by improving properties or reducing costs. It should be remembered that value typically identified by multiple various criteria (Meskanen 2017, p. 9). Value analysis aims to answers the following questions:

- What is it?
- What does it do?
- What does it cost?
- What other options there are for doing the same thing?
- How much these options costs?

(paraphrased from Meskanen 2017, p. 6.)

Answers to these questions are derived from the following different phases included in typical value analysis:

1. Gathering information
2. Analysis
3. Coming up with ideas
4. Evaluation
5. Designing
6. Implementation
7. Observation

(paraphrased from Meskanen 2017, p. 6.)

Value analysis of this study includes phases 1–5, although designing phase is performed at concept level and detailed design phase will follow this study in case target company decides to invest in recommended manufacturing concept. Ideas included in value analysis are based on cooperation between suppliers and OEMs instead of generating totally new ideas. Goyal & Grover stated also that for early adapters of new technology, it is recommended to proceed this way to avoid problems that are commonly known by industry experts (Goyal & Grover 2012, p. 259). Requirements for investment were presented to suppliers and further discussions about details of impeller balancing took place. Final decision of manufacturing concepts included in this study was made by the researcher.

Evaluation criteria of value analysis were derived from requirements list, that was approved by development manager of target company. Three main criteria were identified and divided into sub-criteria which was necessary for analytical approach. Criteria are illustrated in table 1.

Table 1. Evaluation criteria of value analysis. Flexibility, performance and durability were chosen as main criteria. Criteria are derived from requirements list.

EVALUATION CRITERIA OF VALUE ANALYSIS
Flexibility
impeller size scope
material removal capacity
fixture & clamping capability
key automation ratio
Performance
lead time
measure uncertainty
machining accuracy
need of preparations for changing impeller type
Durability
machining tool wear
wear of rotating components
calibration need
scope of maintenance

Flexibility describes the ability to adapt to impellers of different design, material and size while maximizing the level of automation. Performance describes production efficiency and ability to perform manufacturing stages with high quality. Durability evaluates lifetime and maintenance need of concepts. Pairwise comparison of main evaluation criteria was done to give weight factors according to criterion's importance. Each criterion was compared to each other and weight factors were given according to table 2.

Table 2. Pairwise comparison for determining weight factors for evaluation criteria. Weights were approved by development manager of target company. More important than other criterion = + 2 points, comparison to itself = + 1 point.

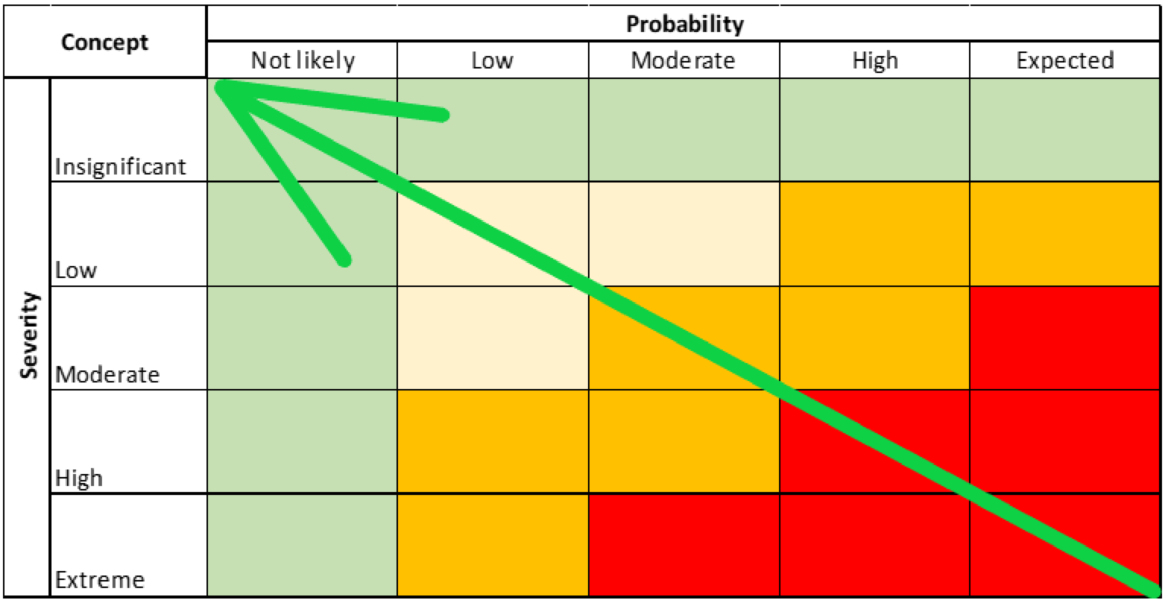
	Flexibility	Performance	Durability	Weight
Flexibility (F)	F	F	F	5
Performance (P)	F	P	P	3
Durability (D)	F	P	D	1

For each sub-criterion, points were given between 1–5, the higher number indicating better grade. Grade for main criteria was formed by calculating geometric average of grades of sub-criteria. Geometric averages of main criteria were multiplied with weight factors given and finally the sum of weighted geometric averages represented total points of concept properties. Finally, points gained based on properties were divided with relative costs (RC) of manufacturing concepts which represented the value of concept. Grading system of value analysis is presented comprehensively in appendix 2.

3.2.2 Risk analysis of manufacturing concepts

First, the most significant risks for automatization of impeller balancing, their possible consequences, and risk management methods were identified. Identified risks were then placed in risk matrix according to their risk priority classes (RPC). RPC's are based probabilities and severities for each concept. Utilized risk matrix is presented in table 3.

Table 3. Risk matrix utilized for identifying RPC's. Red RPC = prevent, orange RPC = minimize, yellow RPC = consider if need to minimize, green RPC = tolerate.



Priority of risk and therefore also RPC decreases in direction of the green arrow drawn in table 3. Risk priority number (RPN) is then calculated as table 4 shows.

Table 4. Calculation of RPN based on RPC's identified in risk matrix.

RPC	**Priority weight**	**No. of risks (10 risks identified)**	**RPN (max 100)**
Red	10	x_1	$10 \cdot x_1$
Orange	7	x_2	$7 \cdot x_2$
Yellow	4	x_3	$4 \cdot x_3$
Green	1	x_4	$1 \cdot x_4$
			$\sum = RPN$

As table 4 shows, number of risks in specific RPC is multiplied by priority weight of RPC. Bigger RPN represents increased risk level. Relative risk levels calculated for each concept are direct relations of RPN's.

3.2.3 Adjusting value to relative risk level

Values obtained from value analysis are finally adjusted to relative risk levels obtained from risk analysis. Investment recommendation is given for the most valuable manufacturing concept based on result of equation 7:

$$Value\ /\ Relative\ risk\ level \quad (7)$$

In equation 7, value is obtained from value analysis by dividing property points with relative costs and relative risk level is obtained from risk analysis as direct relation of RPN's between concepts.

3.2.4 Comparison to current status of balancing

Comparison to current status of balancing was based on examples given for financial measures. Given examples were supported by intangible aspects, which formed the basis of comparison to current status, as real values for financial comparison were not available.

3.3 Verification of automatic unbalance correction

A practical test was performed to verify that the most challenging and restricting phase of automatic impeller balancing, unbalance correction, works in practice and to collect more data about aspects that should be considered in detailed design phase. The most common impeller model balanced in 2018 was chosen as a test piece. Average initial unbalance (120 g) of chosen impeller model was created by grinding material off from impeller's hydraulic surface on frontside of impeller. Hydraulic surface was chosen because permissible material removal area on backside of impeller had to remain unchanged to test automatic correction by milling in a realistic situation. Amount of unbalance and its angular position was measured with current balancing machine. Angular position was marked onto impeller surface with marker pen. Algorithm to calculate milling depth according to amount of unbalance was generated in Microsoft Excel and experimental milling area to remove unbalance was modeled with SolidWorks. Calculations can be found in appendix 3. The principle of created correction algorithm was to use always two correction passages next to each other. Correction passages were selected based on angular position of unbalance; correction was done to passages where angular position of unbalance was between centroids of both passages. To simplify calculations, milling area was kept identical for every correction passage of the specific impeller and milling depth was changed according to amount and angular position of unbalance. Horizontal distance between impeller's designed center of mass and milling area's center of face was used as radius of correction. Angular zero position was set to tip of random back vane.

Conducting practical test was essential to ensure that automatic milling works in practice and to understand what aspect should be considered in detailed design phase of automatic correction. Practical test aimed also to improve reliability of this study and work as a background case for detailed design phase.

4 PROCESS PUMP IMPELLER BALANCING AT TARGET COMPANY

Process pump impeller properties and operation of balancing cell at target company is examined to identify the most significant aspects and elements where value could be added. Impeller scope was limited to the most popular process pump product family's sizes 1–7. During semi-structured interviews of balancing employees, it was found out that improvements were hoped mainly regarding heavy manual grinding work, ventilation of balancing cell and documentation of balancing results (Semi-structured interviews 2019). Increasing automation was identified as a potential way of adding value to balancing cell as it could eliminate all the previously described challenges.

4.1 Process pump impeller types

Process pumps are categorized in seven different sizes according to their bearing sizes. In addition, there exist different range types of pumps which are designed for different operating conditions. (End suction single stage centrifugal pumps 2018, p. 9) To operate fluently in specific conditions, impellers have different hydraulic designs and impeller diameters can be trimmed to different sizes. Figure 7 illustrates examples of different impeller types available that belong to the group of most popular pump ranges of target company.

Figure 7. Examples of different impeller types. (End suction single stage centrifugal pumps 2018, p. 6).

As figure 7 shows, there are various complex impeller designs. This means that balancing, specifically correction, fixing and clamping, cannot be performed the same way with every impeller and thus automatization requires artificial intelligence (AI) to recognize different situations. Table 5 shows key dimension and weight variations of open impeller designs of range type A.

Table 5. Dimension and weight variations of open impellers of range type A (company internal sources). Minimum scope for automated balancing cell is highlighted in blue. Values may differ between different impeller range types.

Bearing size	**Min. weight (kg)**	**Max. weight (kg)**	**Min. diameter (mm)**	**Max. diameter (mm)**	**Min. height (mm)**	**Max. height (mm)**
1	2,5	3,8	115	210	46	55
2	3,5	11	140	330	62	70
3	8,8	21	200	400	91,3	99
4	21	43,8	275	410	176	224
5	47,8	88,5	365	625	217	254
6	97,3	161,3	440	635	306,6	350
7	147,3	398	605	820	309	467
Variation range	**weight: 2,5 – 398 kg**		**diameter: 115 – 820 mm**		**height: 46 – 467 mm**	

As table 5 shows, variation for weight is 2,5–398 kg, for diameters 115–820 mm and for height 46–467 mm. This kind of variation combined with different impeller designs and various permissible correction areas makes automatization of balancing cell challenging. Thus, it may be that the scope of impellers is limited for some of automated manufacturing concepts due to requirements of machinery and CAM- (computer-aided manufacturing) programming. Minimum scope was set to sizes 4–5 including also other pump ranges where minimum and maximum values of weights and dimensions may differ slightly from table 5. It should be noticed that structural material of impeller affects also weight of impeller and sets requirements for material removal. Additionally, casting as impellers' manufacturing method creates variation in dimensions, shapes and weights of actual casted parts when comparing to designed properties.

4.2 Impeller balancing at target company

There exist two balancing cells for process pump impellers at target company. One cell is capable of balancing impeller sizes 4–5 and the other sizes 6–7. Sizes 1–3 and some models of size 4 are balanced at a subcontractor plant. There are currently 10 employees in work shift rotation of balancing, which means that each employee does one week of balancing every tenth week. Balancing procedure follows company's internal work instructions and applied standards. Balance quality requirements are classified by using balance quality grades G defined in SFS-ISO 21940-11. Grades used for target company’s impellers are G 6.3, G 2.5 and in special occasions G 1.0, although most of the balancing is done according to G 6.3 (Semi-structured interviews 2019). Figure 8 illustrates structure of the most commonly balanced process pump impeller in 2018.

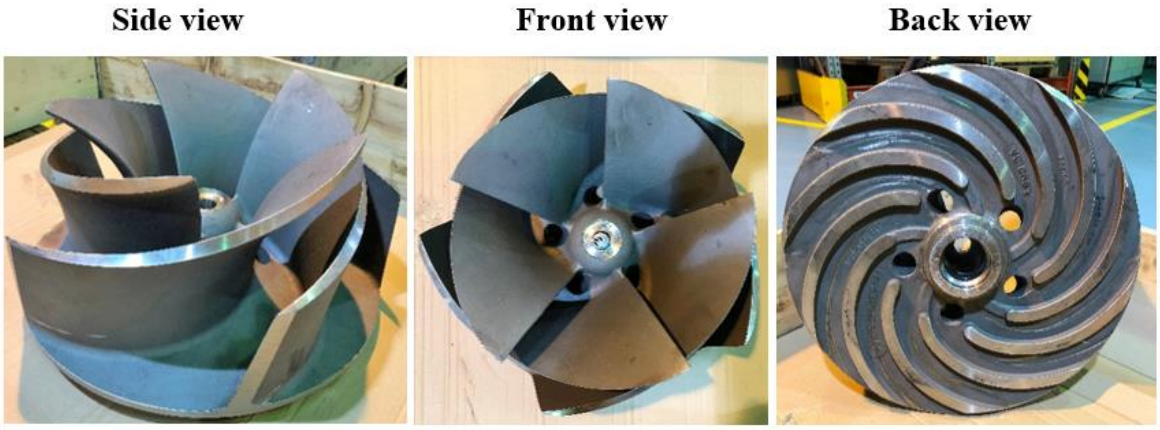


Figure 8. The most commonly balanced process pump impeller in 2018 at target company.

As figure 8 shows, challenges may occur in automatic material handling due to complexity of impellers. Additionally, permissible material removal area for unbalance correction is on the backside of impeller that is facing downwards in balancing machine, which means that there is no room for machine tool access. Therefore, impeller must be detached and turned around or at least lifted to make automatic correction possible.

4.2.1 Internal balancing guidelines and restrictions

To keep hydraulic performance of impeller optimal and ensure operational reliability, applied guidelines and restrictions in balancing must be followed strictly. The most significant restrictions in terms of automatization of balancing are in permissible material removal area for correction. Correction planes for single-plane and two-plane balancing of semi-open impeller are illustrated in figure 9.

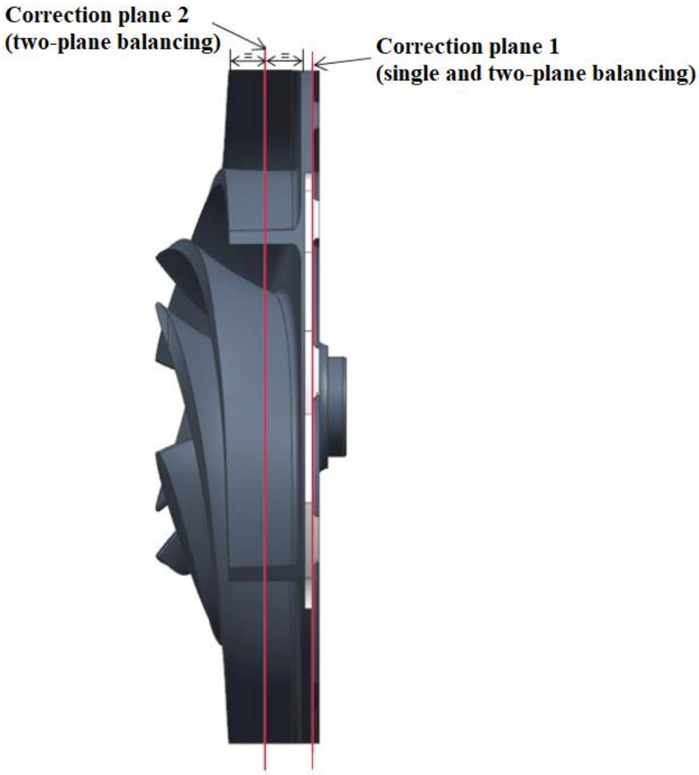


Figure 9. Correction planes used in single- and two-plane balancing for semi-open impellers (paraphrased from company internal sources).

In case of two-plane balancing, material is removed from planes 1 and 2 as shown in figure 9. Plane 2 is located halfway the height of front vane. Automatic correction is targeted only for plane 1 used in single-plane balancing, as most of the balancing cases are single-plane. Additionally, automatization of two-plane correction would increase the complexity of automation significantly due to curved shapes and strict quality requirements of front vanes. This is mainly because geometries of front vanes are essential for hydraulic performance of pump. Figure 10 presents permissible material removal areas for correction in single-plane balancing.

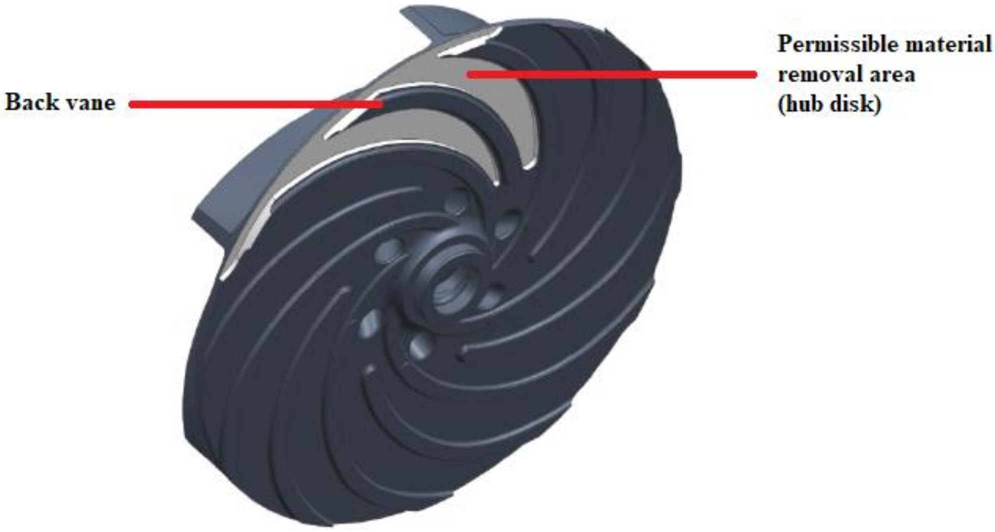


Figure 10. Correction in single-plane balancing is permitted from hub disk area between the back vanes, while back vanes must remain as designed (paraphrased from company internal sources).

As can be seen from figure 10, permissible material removal areas for correction are on the backside of impeller, between back vanes. These areas are now on referred to as correction passages. Removing material from back vanes is prohibited to ensure that operational reliability and hydraulic performance remain as designed. Correction passages in plane 1 are relatively narrow in comparison to grinding tools typically used for correction. When removing material, hub disk must be left minimum 1/3 or 2 mm of original hub disk thickness, as described by following conditions in equation 8: (paraphrased from company internal sources)

$$t_2 \geq \frac{1}{3} \cdot t_1 \text{ [mm]} \quad \& \quad t_2 \geq 2 \text{ [mm]} \qquad (8)$$

In equation 8, t_2 = hub disk thickness after correction and t_1 = original hub disk thickness (paraphrased from company internal sources). Because of conditions presented in equation 8, big unbalance masses in impellers with thin hub disks may cause challenges in correction.

Correction is performed mostly by manually grinding with angle grinder, which is why high precision and physical endurance is required from employee and impeller quality and lead time are related to employee's performance. Manual lathe or manual mill are occasionally used in case there is a need to remove larger amount of unbalance. Manual grinding and milling follow the guidelines presented previously in this chapter. Correction with manual lathe is performed by fixing impeller eccentrically to lathe so that shape of crescent illustrated in figure 11 is created by turning.

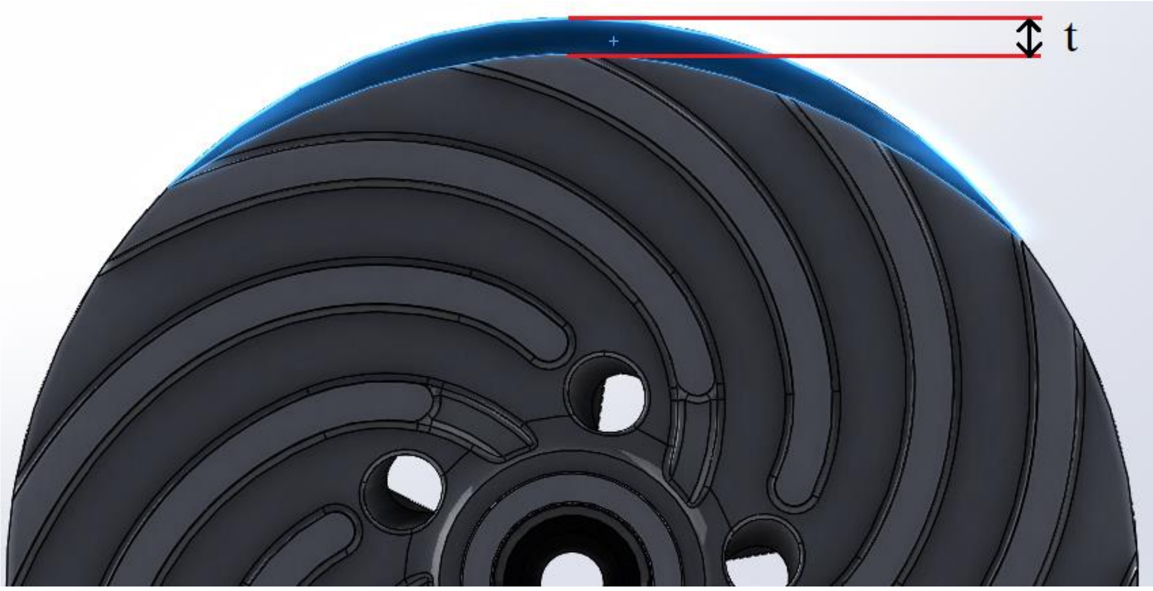


Figure 11. Example of permissible correction area with eccentric turning is illustrated in blue (paraphrased from company internal sources).

In eccentric turning, material removal is allowed from back vanes and hub disk with a limitation that correction width (t) in figure 11 is maximum two percent of impeller diameter. Limitation is presented as equation 9: (paraphrased from company internal sources.)

$$t_{max} = 0{,}02 \cdot d_{imp} \qquad [\text{mm}] \qquad (9)$$

In equation 9, t_{max} = maximum correction width by eccentric turning and d_{imp} = impeller diameter (paraphrased from company internal sources). It is more challenging to identify material removal rate for turning than for milling or grinding, as for different angular positions of unbalance it will remove different amount of material from back vanes. Simply put, removal areas in eccentric turning are not symmetric for every angular position as in milling or grinding.

4.2.2 Examining balancing cells

The possibilities of using existing balancing machinery at target company and integrating automated CNC (computer numerical control) machine were examined. This way investment costs could have been reduced significantly in comparison to investing for a whole new balancing machinery. As figure 11 illustrated, correction passages are curvy and narrow while back vanes must remain untouched, which causes significant challenges and expenses for identifying machining path for NC (numerically controlled) -tool. It also causes challenges for the actual machining. (Pirttilahti 2019.) It turned out that existing machinery would not be able to identify the machining path for automatic material removal with NC-tool. In addition, impellers are fixed front side on top, which means machine tool cannot access correction passages facing downwards. (Semi-structured interviews 2019; Pirttilahti 2019.) Table 6 indicates key statistics collected from impeller balancing for two months.

Table 6. Key statistics of impeller balancing from two months period. Impeller sizes 1–3 are usually balanced at subcontractor plant which is the reason for such small sample size. $U_{initial}$ *= initial unbalance,* U_{per} *= permissible residual unbalance.*

Pump size	Sample size (pc)	Average $U_{initial}$ (g)	Average U_{per} (g)	Impellers with $U_{initial} > U_{per}$ (%)
1-3	7	15,6	0,3	100
4-5	198	98,3	8,0	98,0
6-7	11	275,4	15,6	100

As table 6 indicates, average initial unbalance ($U_{initial}$) varies significantly between different pump sizes, which is directly proportional to the amount of material to be removed. $U_{initial}$ describes the amount of unbalance in a rotor before balancing (SFS-ISO 21940-2 2017, p. 9). Balancing of sizes 1–3 requires accurate measuring machines because of average permissible residual unbalance (U_{per}) as small as 0,3 g. Therefore, it is likely that measuring unbalance cannot be performed with a single machine to all sizes with sufficient accuracy when considering the weight limitations and measuring accuracy in balancing machines. Unbalance correction need is described by percentage of impellers with $U_{initial}$ greater than U_{per}. As table 6 shows, correction must be performed for nearly every impeller. Due to high variation of impeller types and properties, average impeller balancing case shown in table 7 was formed based on statistical analysis of balancing data.

Table 7. Average impeller balancing case used to evaluate and compare new manufacturing concepts for automatic balancing.

Impeller size	5
Average $U_{initial}$ (g) (sample size: 58)	120
weight (kg)	58,2
diameter (mm)	455

The most commonly balanced process pump impeller at target company in 2018 was selected as reference impeller in table 7. Average $U_{initial}$ of 120 g was calculated based on sample size of 58 impellers of size 5.

Figure 12 illustrates production share of balancing at target company's factory from two months period.

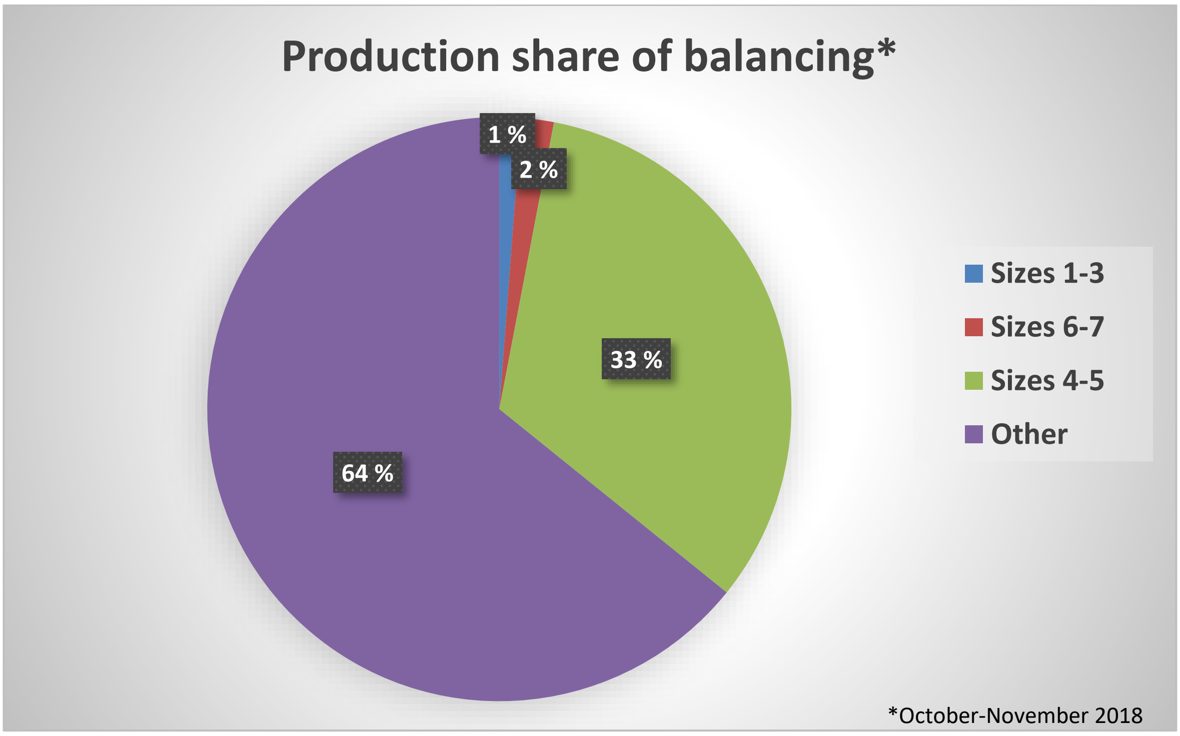


Figure 12. Production share of balancing from two months period.

As figure 12 shows, sizes 4–5 cover one third of production share in balancing. Category of other impellers describes the share of impellers that are not considered in the scope of automatization of balancing during this study. It should be noted that some of the other pump impellers may have shorter lead times which should be accounted in comparing production shares.

Two operationally similar balancing cells exist for process pump impellers; cell 1 for pump sizes 4–5 and cell 2 for sizes 6–7. As figure 12 illustrated, utilization rate of cell 1 is significantly higher than of cell 2, which is why cell 1 is used as a reference cell in this study. In cell 1 there are two balancing machines. One balancing machine is used for measuring unbalance of impeller sizes 4–5 and the other only for impellers of other pump types. There exists station for unbalance correction, where material is removed manually with angle grinder. Angle grinders are stored in tool holders and there is cabinet for storing impeller fixture adapters and spare parts. Air filtration and ventilation system is connected to the cell and heist is used for moving impellers. Impellers coming to balancing are stored in front of balancing cell, near the computer used for setting up balancing parameters. Balancing results are documented hand-written to balancing log at desk next to computer. Figure 13 depicts cell layout of balancing cell for impeller sizes 4–5.

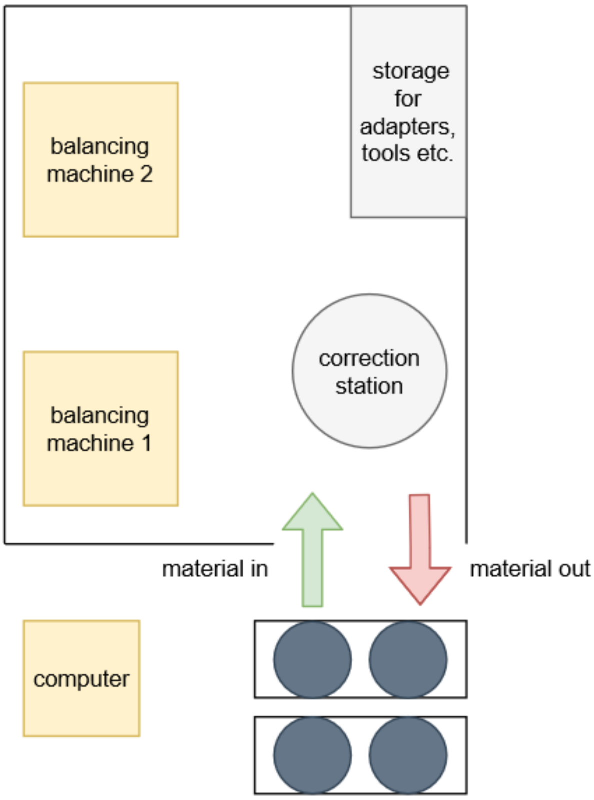


Figure 13. Cell layout of balancing cell for impeller sizes 4–5.

Balancing cell shown in figure 13 includes also manually operated heist system for moving impellers. In cell 2, balancing machine is used for measuring unbalance of process pump impeller sizes 6 and 7. Otherwise cell 2 layout principle is close to cell 1 but includes only one balancing machine and doesn't include computer.

4.2.3 Operation in balancing cell

At first, essential impeller information is documented manually on hand-written production log. Information consists of part identification number, sales reference number, weight and permissible residual unbalance U_{per} as an example. U_{per} is calculated with a specific program according to input parameters. Then impeller is transferred to unbalance measuring machine and radius of correction (equal to radius of impeller) is inserted to the machine. Amount and angular position of unbalance is measured, $U_{initial}$ is documented, and angle of unbalance marked to impeller surface with marker pen. If $U_{initial}$ is greater than U_{per}, impeller is transferred for correction table nearby. Correction is done mostly by removing material manually with angle grinder or in some cases with manual lathe or manual mill. Measuring-correction cycle is repeated until residual unbalance is lower than U_{per} according to given balance quality grade G. Employee must evaluate visually the amount of material removed in correction, which increases the probability of repeating the cycle.

There are totally 10 employees in weekly work shift rotation of balancing. This means that the same employee performs impeller balancing every 10^{th} week. Therefore, at the beginning of every work week, it may take a while for the employee to memorize details of balancing process which may cause excessive measuring-correction cycles. It can be concluded that manual correction with angle grinder requires high precision and physical endurance from employee, as one must be careful not to hit surfaces already machined or surfaces vital for hydraulic performance of impeller with rotating abrasive disc of angle grinder. It may cause challenges as correction passages are relatively small when considering the sizes of abrasive tools. Employees' work experience in balancing has also significant effect in efficiency of balancing. If employee is inexperienced, misjudgments in grinding and visual evaluation of amount of material removed may lead to repeated measuring-correction cycles. (Semi-structured interviews 2019.) Figure 14 depicts main stages of current impeller balancing process at target company.

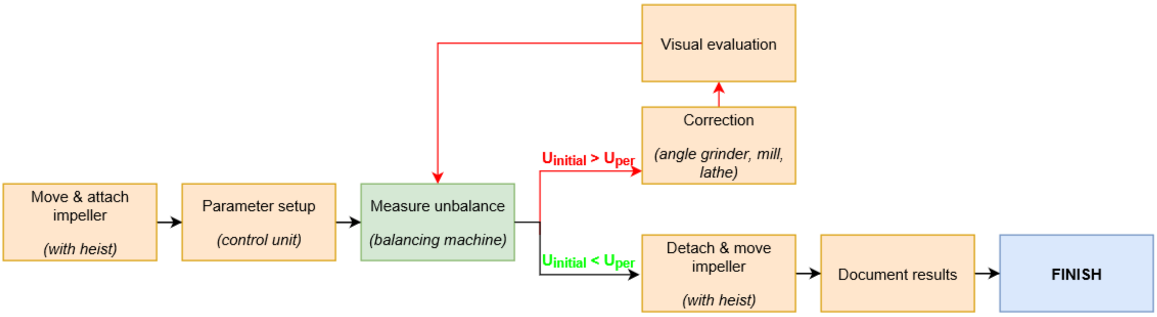


Figure 14. Key stages of current impeller balancing process at target company. $U_{initial}$ = initial unbalance, U_{per} = permissible residual unbalance, orange box = manually operated function, green box = automatically operated function, red arrow = negative workflow.

In figure 14, measuring-correction cycle illustrated with red arrows causes negative workflow and must be performed until measured residual unbalance U_{res} is below U_{per} according to chosen balance quality grade G in SFS-ISO 21940-11.

4.3 Summary of impeller balancing at target company

Amount of heavy manual work in current balancing procedure is relatively high while quality requirements for balancing are strict. Lead time and quality are significantly dependent of employee's performance, as high precision and physical endurance are required in challenging working conditions. The most challenging work phases are manual unbalance correction and visual evaluation of correction result that is a reason for excessive measuring-correction cycles. These phases must be set as focus points for adding value. In addition to correction and visual evaluation, moving and fixing impellers and data documentation were found essential work phases to be automated. In conclusion, increasing automation is potential way of adding value to balancing process in many terms, such as improving lead time, impeller quality, working conditions and occupational safety.

5 COMPARISON OF POTENTIAL MANUFACTURING CONCEPTS FOR AUTOMATIZATION OF IMPELLER BALANCING

This chapter examines and compares new manufacturing concepts for automatization of impeller balancing process. In addition to balancing, possibilities to include automatized impeller trimming to new balancing cell were examined as it would increase efficiency and functional flexibility of new cell. Impeller trimming refers to procedure where impeller diameter is downsized by turning. Impeller trimming is performed in cases where it improves pump characteristics to match better the operating conditions in end-user application.

5.1 Pre-comparison of different concept categories

The main purpose of any kind of investment is to add value for the investor. As stated previously, value can be added by improving properties or reducing costs. Value of impeller balancing cell is a combination of various criteria, which are included in value analysis in this study. During data collection phase, ideas for adding value were categorized by their level of automation and size of investment:

- Category 1 – small investments without automation: for example, designing new impeller fixture, developing manual working methods or developing existing tools and machines.
- Category 2 – medium size investments by semi-automatic solutions: for example, manually controlled articulated arm for unbalance correction or manually controlled milling unit integrated to balancing cell.
- Category 3 – large size investments aiming for full automatization: for example, utilize fully automatic solutions to maximize automation level in balancing cell, utilize advanced manufacturing technology.

Pre-comparison was done to find the most effective category to increase value of impeller balancing. Even though increasing automation has been assumed as primary way to increase value, category 1 consisting of small investments without automation is included in pre-comparison to verify that automation truly is the most effective way of increasing value. This kind of pre-comparison was required, as semi-structured interviews of balancing employees at target company indicated that there exist also other ways to increase value than maximizing automation (Semi-structured interviews 2019). Pre-comparison of different categories is done by evaluating how value-reducing factors of existing balancing cell could be compensated. Pre-comparison is illustrated in table 8.

Table 8. Illustration of how well different categories could eliminate the disadvantages of existing balancing process. Disadvantages are based on semi-structured interviews of balancing employees, discussions with development manager and own observations of the researcher. Red cross = disadvantage remains unchanged in the category, yellow cross = reduced negative effect of disadvantage, no cross = disadvantage removed.

Disadvantages of existing balancing process	**Existing**	**Category 1**	**Category 2**	**Category 3**
Exposure to hazardous metal dust	X	X	X	
Need to evaluate material removal rate visually	X	X	X	
Heavy manual work in correction	X	X	X	
Quality related to experience, precision and physical endurance of employee	X	X	X	
Lead time related to experience, precision and physical endurance of employee	X	X	X	
Considerable risk of injury during normal operation	X	X	X	
Manual reporting of balancing results	X	X	X	
Need to move impeller manually for correction	X		X	
Short technical lifetime	X	X	X	

As table 8 indicates, new fully automatic cell (category 3) could eliminate all the cons in best scenario. Semi-automatic solutions (category 2) could reduce the heaviness of manual work and effect of employee to quality and lead time. Significant benefits for category 1 were not recognized in comparison to other categories. In conclusion, comparison of potential manufacturing concepts will focus on comparing solutions with maximized level of automation for balancing.

5.2 Requirements for investment

Requirements list presented in table 9 was formed together with the researcher and development manager of target company. Adjustments were made to the list during background study. List was ultimately approved by development manager.

Table 9. Requirements list for the investment. D = demand, W = wish.

PROPERTY	D / W
Functions	
single-plane unbalance measuring	D
two-plane unbalance measuring	W
automatic single-plane correction	D
automatic bur removal	D
impeller trimming	W
automatic workpiece handling	W
automatic documentation of balancing results	W
Quality & speed	
balance quality grade G 6.3	D
balance quality grade G 2.5	W
balance quality grade G 1.0	W
quality independent of employee's performance	D
quality improved	D
quality constant	D
lead time independent of employee's performance	D
lead time reduction	D
increased production capacity	D
quick setup for changing impeller type	W
Flexibility	
adaptability to impeller size scope 4–5	D
adaptability to impeller size scope 1–5	W
adaptability to impeller size scope 1–7	W
impeller material scope unlimited	W
Durability	
sufficient machinery lifetime	D
sufficient machining tool lifetime	D
sufficient need of maintenance	D
minimized energy consumption	W
Working conditions	
improved working conditions	D
easy user interface	W
minimized amount of manual work	W
minimized risk of physical injury during normal operation	W
no direct exposure to hazardous materials	W
Financial	
Payback time max. 10 years	D
Payback time max. 3 years	W

As table 9 describes, requirements are divided into six main categories. Diameter trimming was wished as additional feature to increase efficiency and functional flexibility of new cell. Requirements list works as a basis for deriving evaluation criteria of value analysis. Based on background study, key functions to be automatized are listed as follows:

- unbalance correction
- bur removal after correction
- diameter trimming
- moving workpiece
- attaching workpiece
- data documentation

It should be noted that details presented in the following chapters describing new manufacturing concepts may change in the detailed design phase conducted after this study. Such details are for example automation level of each concept and final structure of presented machinery. Presented details of concepts are derived from preliminary quotations and discussions with suppliers and other commercial sources. The purpose is to illustrate automation potential of each concept and capability of responding to requirements list.

5.3 Manufacturing concept 1

Manufacturing concept 1 consists of balancing machine with integrated CNC-milling unit and control unit for parameter setting. Integrated solution of unbalance measuring and correction to same machine was included in comparison, as it allows a simple and compact cell layout and need of moving impellers could be kept minimal. Possibility of integrating diameter turning to same machine was researched, but concept 1 proved to be inadequate for it. Table 10 shows main machinery included in preliminary quotation of concept 1 made by supplier 1.

Table 10. Main machinery included preliminary quotation of manufacturing concept 1. (paraphrasing Quotation and specifications of supplier 1 2019.)

Machinery	**Manufacturing stages & functionality**
balancing machine with integrated milling unit	measuring unbalance, unbalance correction
control unit with required software	controlling, parameter setting, data management

As table 10 shows, measuring unbalance and correction are performed in one machine, which enables simplified cell layout for concept 1. Manipulator for moving and lifting impellers should be included in cell, but it is likely that concept 1 could be integrated with the heist system in current balancing cell. Figure 15 presents an example structure of balancing machine with integrated milling unit.

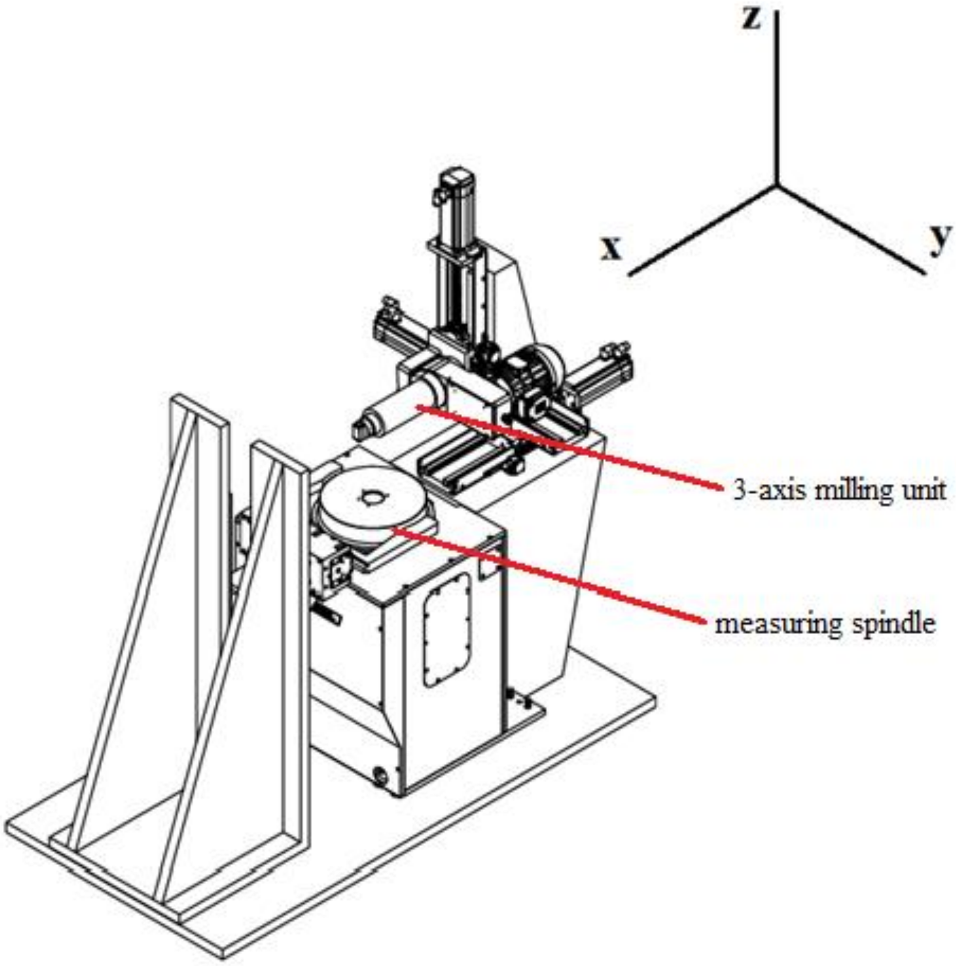


Figure 15. Example structure of vertical balancing machine with integrated vertical milling unit. Structure is vulnerable to changes during detailed design phase. (paraphrasing Quotation attachment of supplier 1 2019.)

As figure 15 illustrates, milling spindle movement is restricted by three axes; two horizontal and one vertical that are controlled by brushless motors. Milling spindle is mounted on horizontal x-axis but has 90 degree milling head to allow milling from vertical direction (z-axis). Unbalance correction begins with vertical movement of milling tool for correct cutting depth and horizontal movement is based on interpolation between x- and y-axis with help of rotating platform. (Quotation and specifications of supplier 1 2019, p. 6; Päkki 2019.)

Electronic control unit has storage for 1000 different rotor data, which is enough considering the variety of impellers at target company (Quotation and specifications of supplier 1 2019, p. 7). Table 11 presents key properties that were available for concept 1.

Table 11. Key properties available for concept 1. Key properties are based on requirements list. (Quotation and specifications 2019; Päkki 2019).

Property	**Value**
Available measuring planes	1
Available automatic correction planes	1
Bur removal capability	manually by operator
Impeller trimming capability	no
Impeller moving capabilities	manually by operator
Data documentation	automatic, transfer via Ethernet
Max. chip thickness in milling	2,5 mm
Amount of automated key functions	2 / 6 (correction, data documentation)
Measure uncertainty	20 gmm (excluding fixture error)
Machining accuracy	± 20 µm
Need of manual preparations for changing impeller type	parameter setup, adapter changing, moving & attaching impeller to machine
Impeller size adaptability	m = 5 – 150 kg d = 150 – 625 mm → size scope 3-5 h < 301 mm
Guaranteed impeller material adaptability in milling	ASTM A890 3A
Energy consumption	spindle drive motor power = 7 kW correction unit motor power = 3,75 kW
User interface type	Windows 10 embedded
Calibration	hard-bearing principle, permanent calibration

As table 11 describes, impeller scope for concept 1 in terms of size and weight capabilities of machinery is sizes 3–5. Machinery is capable of machining ASTM A890 Grade 3A which is the most common material for impellers of target company, but adaptability to other materials with quoted machinery was not indicated and should be examined during detailed design phase.

5.3.1 Operational principle and cell layout of concept 1

In concept 1, employee moves and attaches the workpiece manually to balancing machine with help of manipulator. Any manipulators were not included in quotation of supplier 1 and should be procured separately. Measuring unbalance and unbalance correction happens automatically with human-operated control unit used for parameter setting. Unbalance is measured in balancing machine. Impeller is planned to be lifted in the balancing machine to allow milling tool access to correction plane 1. Bur removal after correction must be performed manually according to quotation of supplier 1. (Quotation and specifications of supplier 1 2019). Figure 16 presents operational flow of manufacturing concept 1.

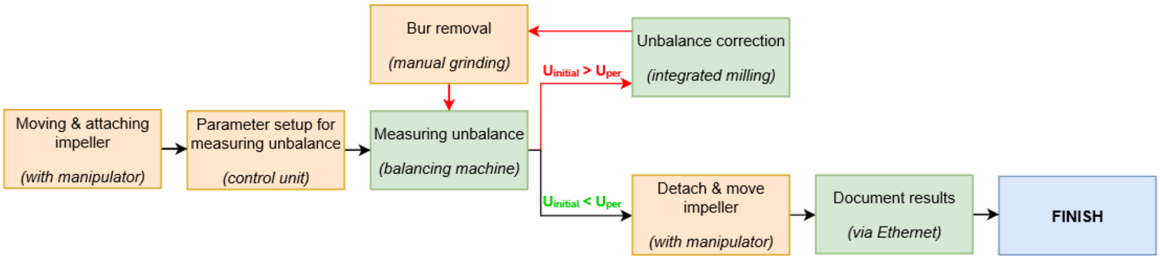


Figure 16. Operation flow chart of manufacturing concept 1. $U_{initial}$ = initial unbalance, U_{per} = permissible residual unbalance. Orange box = manually operated, green box = automatically operated.

As figure 16 illustrates, measuring unbalance, unbalance correction and documenting results are automatically operated functions, of which two of them belong to key functions to be automatized. Figure 17 illustrates cell layout of concept 1.

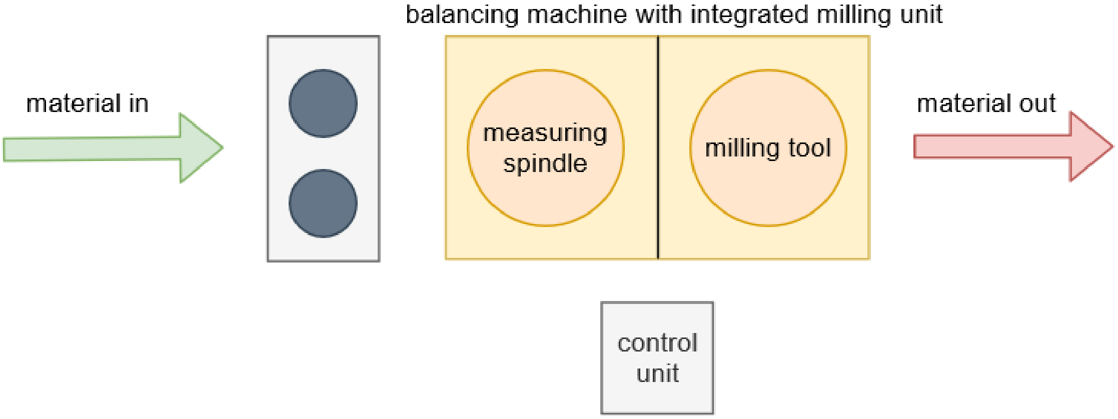


Figure 17. Cell layout of concept 1. Machinery is based on supplier's quotation, but layout illustration is generated solely by the researcher. (paraphrased from supplier 1 quotation.)

As figure 17 shows, cell layout is relatively simple and compact. Need to move impeller is also minimized due to integrated solution of unbalance measuring and correction.

5.4 Manufacturing concept 2

Manufacturing concept 2 consists of separate balancing station and unbalance correction station. Machinery included in preliminary quotation of supplier 2 are described in table 12.

Table 12. Main machinery included in preliminary quotation of manufacturing concept 2. (paraphrasing Quotation and specifications of supplier 2 2019.)

Machinery	**Manufacturing stages & functionality**
balancing machine	measuring unbalance
CNC milling station	unbalance correction
control unit with required software	controlling, parameter setting, data management

As table 12 shows, measuring unbalance and correction are performed with two separate machines. Manipulator for moving and lifting impellers should be included in cell. It is not certain that concept 2 could be integrated with the heist system in current balancing cell, so manipulator should be procured from separate supplier. Figure 18 illustrates machinery included in preliminary quotation of concept 2 by supplier 2.

Figure 18. Balancing machine (left) and unbalance correction station (right). Images are not binding, and machines are subject to changes in detailed design phase. (Quotation and specifications of supplier 2 2019, p. 3.)

Images presented in figure 18 are to illustrate basic structure of machinery. Customization is required in detailed design phase so final structures may differ from the presented, but basic principles follow presented machinery. In concept 2, measuring unbalance and unbalance correction are automated. An example structure for milling spindle is presented in figure 19.

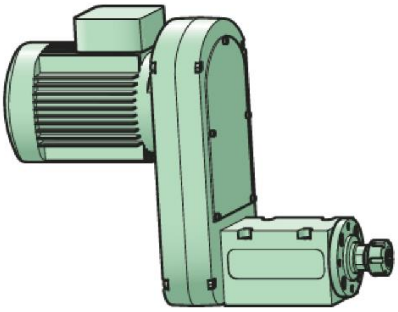


Figure 19. Illustration of mechanical structure of milling spindle. Structure may change during detailed design phase. (paraphrasing Suhner powermaster, p. 4.)

Structure of milling spindle presented in figure 19 is an example of standard milling solution for supplier 2. Modifications are required to match requirements of automatic correction. Table 13 describes key properties that were available for manufacturing concept 2.

Table 13. Key properties available for concept 2. Key properties are based on requirements list. (Quotation and specifications of supplier 2 2019.)

Property	**Value**
Available measuring planes	2
Available automatic correction planes	1
Bur removal capability	manually by operator
Impeller trimming capability	no
Impeller moving capabilities	manually by operator
Data documentation	automatic
Amount of automated key functions	2 / 6 (unbalance correction, data documentation)
Measure uncertainty	single plane: 5-10 gmm two-plane: 20-80 gmm
Given lead time estimations	60-70 sec. for unbalance measuring and correction, excluding moving, attaching and detaching
Impeller size adaptability	weight limitations: 20-400 kg diameter limitations: ≤ 850 mm height limitations: ≤ 450 mm → adaptability to impeller sizes 4-6
Impeller material adaptability	ASTM A890 Grade 3A → OK ASTM A747 Grade CB7Cu-2 → possible, but increases lead time ASTM A532 Class III Type A → possible, but increases lead time
Energy consumption	balancing machine power = ~ 7,5 kW CNC machine power = ~ 10 kW
User interface type / language	Windows 7 embedded
Calibration	hard-bearing principle → permanent calibration

As table 13 shows, estimations of maximum chip thickness in milling or any other measures of machining capability were not available. Key automated functions consist of unbalance correction and data documentation. Impeller material adaptability for the most common structural material ASTM A890 Grade 3A was guaranteed, while adaptability to more challenging materials in terms of machinability, such as ASTM A747 Grade CB7Cu-2 and ASTM A532 Class III Type A, is possible but lead time would be longer and machine tool lifetime reduced.

5.4.1 Operational principle and cell layout of concept 2

Balancing machine can measure unbalance in one or two planes, after which impeller must be moved to correction station. In the correction station, impeller must be turned upside down to allow machine tool access. Figure 20 describes operation flow of manufacturing concept 2.

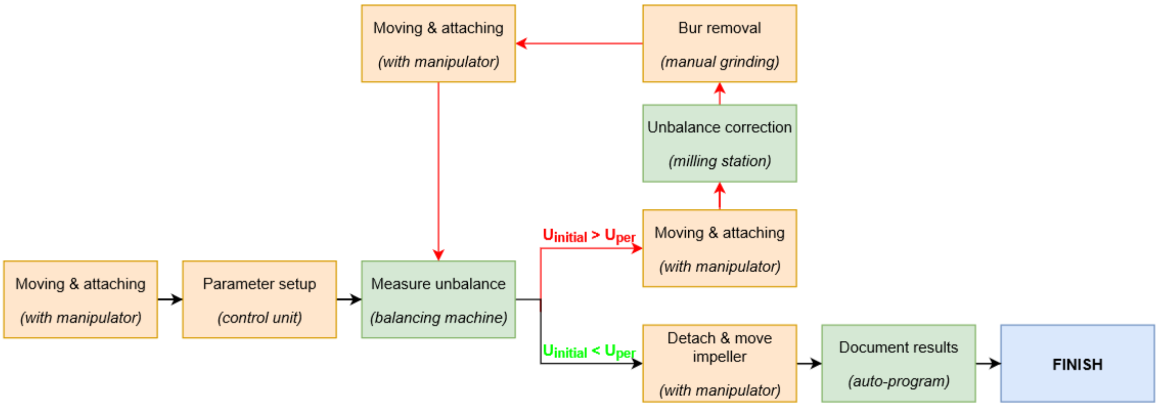


Figure 20. Operation flow chart of manufacturing concept 2. Orange box = manually operated, green box = automatically operated.

As figure 20 illustrates, measuring unbalance, unbalance correction and documenting results are automatically operated functions, of which unbalance correction and documenting results belong to key functions. In comparison to concept 1, separate measuring and correction stations in concept 2 cause two extra moving and attaching phases to be operated manually. Therefore, it is expected that lead time is higher in concept 2. On the other hand, separate measuring and correction stations reduce risk of insufficient measure uncertainty and machining accuracy in comparison to integrated solution of concept 1. Figure 21 illustrates cell layout of concept 2.

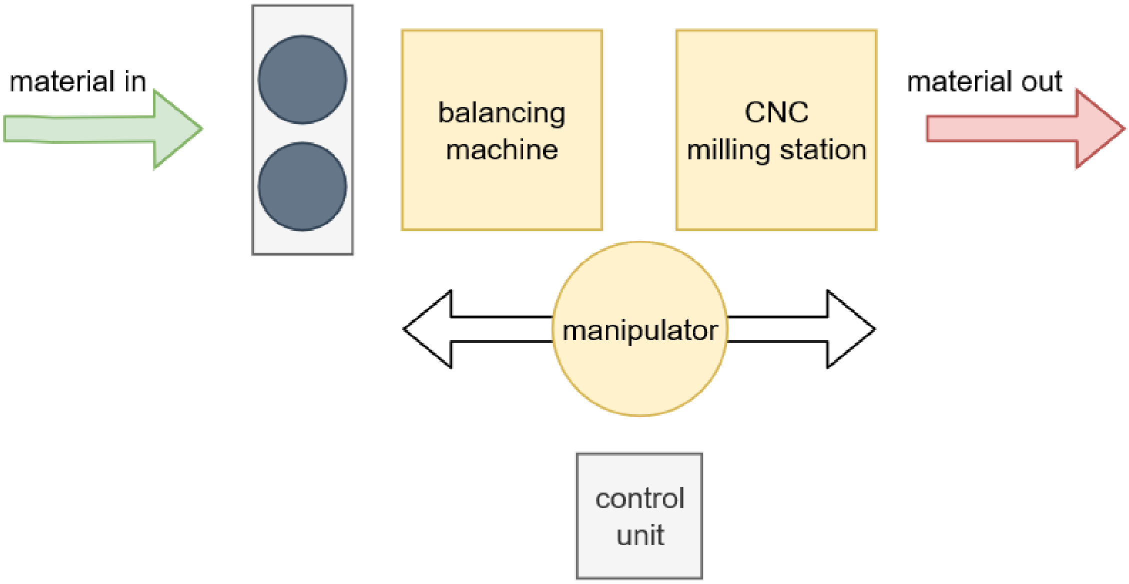


Figure 21. Cell layout of concept 2. Manipulator is not included in supplier 2 quotation. Other machines are based on preliminary quotation of supplier 2. Cell layout is generated solely by the researcher.

Machine scope of concept 2 allows to keep cell layout of figure 21 compact and simple, although it will consume more floor space than concept 1. Manipulator is not included in supplier 2 quotation and should be procured from separate supplier.

5.5 Manufacturing concept 3

Manufacturing concept 3 consists of separate work stations and machines for different functions. All machinery and functions would be controlled through central control unit. Supplier 3 is not OEM for any of machines quoted but is specialized in designing automation and interoperability between quoted machinery. Table 14 shows main machinery include in preliminary quotation of concept 3 by supplier 3.

Table 14. Main machinery included in preliminary quotation of manufacturing concept 3.

Machinery	**Manufacturing stages & functionality**
vertical turning lathe 1	unbalance correction (milling)
vertical turning lathe 2	diameter trimming (turning)
robot manipulator	moving & attaching workpieces
central control unit with required software	operation & parameter controlling, data documentation

As can be noticed from table 14, preliminary quotation does not include balancing machine that should be procured from separate supplier. To enable comparison to other concepts, a recommendation for balancing machine to be combined with concept 3 is given by the researcher. Supplier 3 would still provide all required software to integrate balancing machine to function automatically with other machinery of concept 3. Concept 3 would possibly be capable of handling also shape machining of impeller, in addition to unbalance correction and diameter trimming. This could provide significant additional value for the investment and adaptability to shape machining should be examined during detailed design phase. Table 15 describes key properties that were available for manufacturing concept 3.

Table 15. Key properties available for concept 3. Selected key properties are based requirements list. (Quotation and specifications of supplier 3 2019.)

Property	**Value**
Available measuring planes	2
Available automatic correction planes	1
Bur removal capability	possibilities for automation
Impeller trimming capability	automatic
Impeller moving capabilities	automatic, assisted with machine vision
Data documentation	automatic
Amount of automated key functions	5 / 6 (correction, impeller trimming, moving, attaching, data documentation)
Measure uncertainty	single plane = 10–25 gmm two-plane = 20–50 gmm
Machining accuracy	± 4 µm
Milling tools available	12
Milling tool spindle speed	4000 rpm
Milling tool speed range	infinitely variable
Impeller material adaptability (milling)	ASTM A890 3A at minimum
Calibration of balancing machine	hard-bearing principle: permanent calibration
Energy consumption	energy-saving technology utilized in vertical lathes

Machine recommended for measuring unbalance is a vertical balancing machine with hard bearing principle. It can measure unbalance in two planes with minimum plane distance of 180 mm and the machine is designed for make-to-order products. Weight range varies from 10–300 kg and maximum diameter is 810 mm but with modified protective device it can be extended to 1400 mm and maximum height 450 mm. It has cache memory for 99 rotor data. Correction data can be sent to external milling machine via ASCII – interface (CAB 700), or directly (CAB 920). Milling software is also provided in case needed (VIRIO; VIRIO RM1041-1e, p. 12). Balancing machine is illustrated in figure 22.

Figure 22. Recommended vertical balancing machine for unbalance measurement (VIRIO).

Machine housing of figure 22 balancing machine is made from a mineral casting, which ensures good damping properties and suppresses undesired interference effects and improves thermal stability for consistent measuring conditions (VIRIO RM1041-1e, p. 9). Table 16 describes key technical properties of balancing machine proposed.

Table 16. Key technical properties of proposed vertical balancing machine. (VIRIO; VIRIO RM1041-1e, p. 12.)

Min. weight of rotor	10 kg
Max weight of rotor incl. adapter /clamping tooling	300 kg
Max. rotor height	450 mm (can be adjusted on request)
Max rotor diameter	810 mm 1400 mm (with modified protective device)
Max measuring speed	600 rpm
Measuring uncertainty	single plane balancing: 10-25 gmm two-plane balancing: 20-50 gmm
Min. measuring plane distance (two-plane balancing)	180 mm
Measuring unit calibration	permanent

To enable both impeller unbalance correction and diameter trimming, vertical turning lathes were proposed for concept 3 by supplier 3. In this case, balancing cell requires separate balancing machine, workpiece handling unit and control unit. Thus, interoperability between different machines requires planning, specifically when machines are manufactured by different companies. Also, Safaieh, Nassehi and Newman (2012, p. 79) identify cross-technology interoperability in CNC machining as a research gap in their study. This emphasizes the importance of detailed design phase in concept 3. Commercial example of vertical turning lathe is presented in figure 23.

Figure 23. Commercial proposal of vertical turning lathe. (Quotation and specifications of supplier 3 2019.)

OEM of vertical turning lathe in figure 23 provides a specific preventive maintenance checklist to minimize downtime of their CNC machines. Checklist includes inspections to be made daily, weekly, every three months, every six months and yearly. Inspection recommendations are given also in hours of operation. Daily check recommendations include for example hydraulic pressure, hydraulic fluid level, cleaning chips out of chip pan and lubrication. Yearly checks should be made by a local distributor and include for example checking headstock for taper, checking spindle for radial and end play and checking the chuck cylinder for run out. (Williams, 2013) Full preventative maintenance check list is presented in appendix 4.

Vertical turning lathe of figure 23 utilizes also cutting-edge energy-saving technology to optimize energy consumption both during idle time and when machining. Calculations based on actual power measurements stated that power savings of 74 % (171 kWh) during idle time and 9 % (36 kWh) during machining could be achieved in one month. Although, it must be acknowledged that power consumption levels are dependent of machine specifications and operating conditions. (Energy-Efficient Machine Tool Technologies, For Any Size Shop 2016, p. 4.)

5.5.1 Operational principle and cell layout of concept 3

Operation of manufacturing concept 3 provides high level of automation and functionality, as diameter trimming is included in addition to balancing. Impeller trimming leaves bur on impeller which should be removed before measuring unbalance. Bur removal method remained unsolved during the study and must be examined during detailed design phase. Operational principle of manufacturing concept 3 is presented in figure 24.

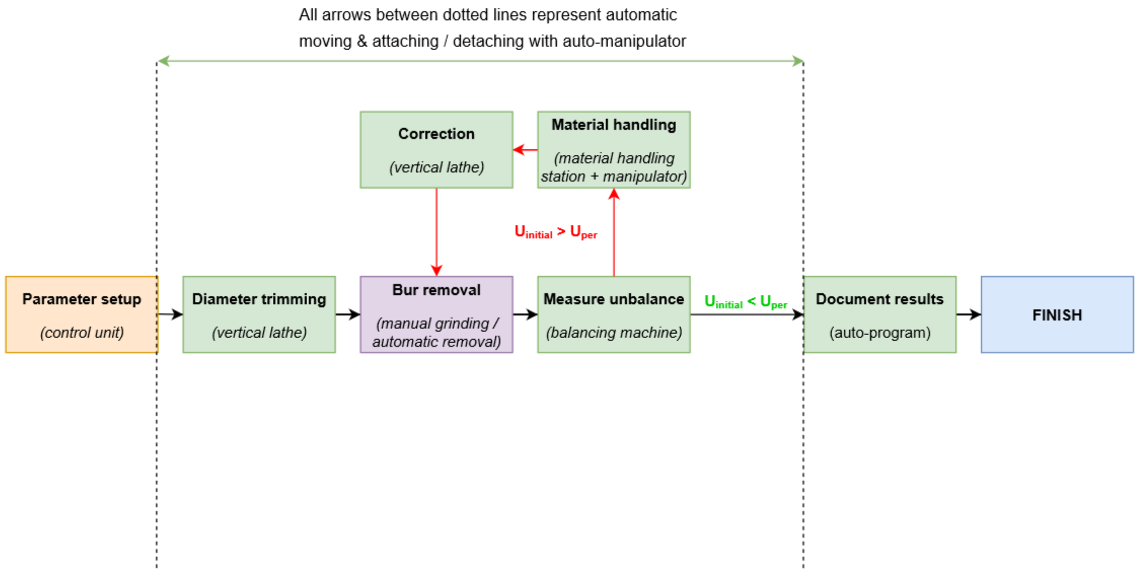


Figure 24. Operation flow chart of manufacturing concept 3. Moving and attaching are performed automatically in every stage and are illustrated by arrows between dotted lines. Orange box = manually operated, green box = automatically operated, purple box = unsolved operation method.

As figure 24 illustrates, moving, attaching and detaching, diameter trimming, unbalance correction and documenting results are automatically operated and belong to key functions to be automatized. Automatization of bur removal remained unsolved during this study. Figure 25 illustrates cell layout of concept 3.

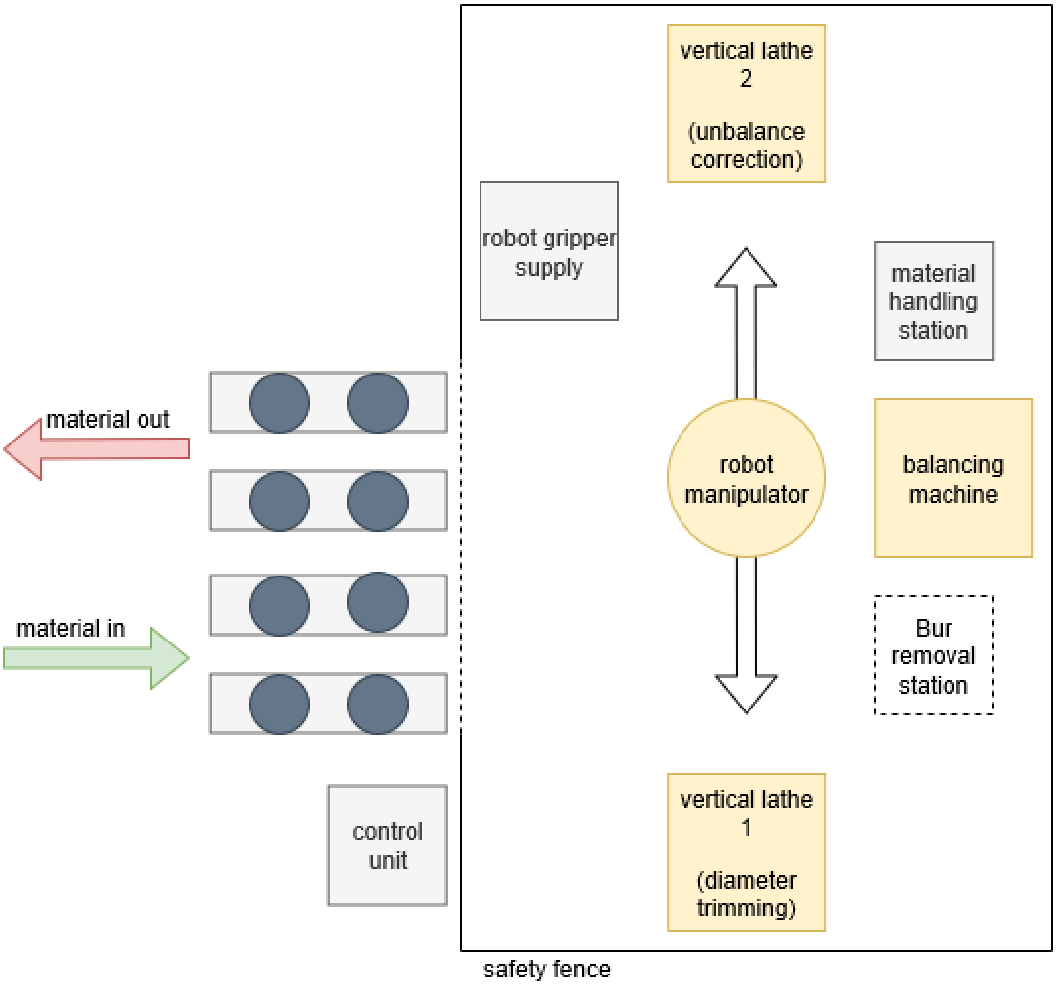


Figure 25. Manufacturing concept 3 cell layout is based on cooperation between researcher and supplier 3. (paraphrased from Quotation attachment of supplier 3 2019.)

As figure 25 shows, concept 3 consists of balancing machine for measuring unbalance, two vertical turning lathes for unbalance correction by milling and diameter trimming by turning and robot manipulator for moving workpieces. Machine vision is utilized for locating incoming material. Material handling station is required for turning over the impeller with robot manipulator, as in diameter trimming and unbalance correction impeller is attached different side up. Bur removal could be automated with help of robot manipulator equipped with a grinding tool as an example. Bur removal could also be performed with vertical lathe, but in this case it was estimated that lead time of cell would be increased significantly in comparison to separate bur removal station. Two vertical lathes are included in cell layout, which is because lead time in diameter trimming is typically longer than in balancing and thus it could create unwanted bottleneck in case of utilizing only one vertical lathe. (Quotation and specifications of supplier 3 2019.)

5.6 Summary of all manufacturing concepts

Operational principles of all manufacturing concepts differ significantly from each other. Structures of machinery varied also, regardless that some of them perform the same function. For example, different models of balancing machines were included in every concept. It should be noted that concept 3 allows to use various models of balancing machines without revising quotations and comparison between the different models of balancing machines should be done to achieve the most suitable concept. For concepts 1 and 2, balancing machine and milling unit models cannot be changed without revising quotations.

Collecting detailed information of concepts 1 and 2 proved to be challenging due to modification need of standard machinery. Concept 3 includes nearly standard machinery of various suppliers and thus more detailed information could be collected. Table 17 summarizes all manufacturing concepts.

Table 17. Summary of all manufacturing concepts. Information of each concept may change during detailed design phase.

	Concept 1	**Concept 2**	**Concept 3**
Quoted key machinery	• balancing machine with integrated milling unit • control unit + software	• balancing machine • milling unit • control unit + software	• 2 x vertical lathes • robot manipulator • control unit + software
Other machinery required (not quoted)	• manipulator (optional)	• manipulator (mandatory)	• balancing machine (mandatory)
Manual work required	• moving • attaching & detaching • bur removal	• moving • attaching & detaching • bur removal	• bur removal

6 VALUE ANALYSIS OF MANUFACTURING CONCEPTS FOR AUTOMATIZATION OF IMPELLER BALANCING

It is essential that evaluation method with a solid foundation is utilized when comparing these kind of advanced manufacturing technology (AMT) systems so that all the pros and cons are considered. Several definitions for AMT are provided by various organizations. Computer-guided operation, technology that enables cost, quality and flexibility improvements in production, or combining production equipment and manufacturing methodologies to increase automation are some characteristics for AMT stated by Garcia & Alvarado. (García & Alvarado 2012, p. 123.) Top four AMTs acquired recently before 2012 were robot, milling unit, vision system and CNC-equipment (García & Alvarado 2012, p. 127). Therefore, manufacturing concepts presented in this study are clearly categorized as AMT systems. It is challenging to select the most suitable concept as several AMTs are available to perform the same operation. In addition, a lack of proper methods to evaluate effectiveness of AMT systems has been recognized. (Goyal & Grover 2012, p. 256.)

This chapter presents value analysis between three different manufacturing concepts for automatization of impeller balancing. To make a solid foundation for evaluating and selecting the most suitable manufacturing concept for impeller balancing, value analysis was combined with risk analysis eventually. This way identified key properties, investment costs and identified key risks were taken into consideration when selecting the most suitable concept.

6.1 Basis of evaluation criteria

As stated before, value consists of multiple factors. Evaluation criteria for automatization of impeller balancing were derived from requirements list that was approved by development manager of target company. Selected evaluation criteria and given weights for each main criterion were also approved by development manager. Table 18 presents evaluation criteria, units of measures and basis of criteria.

*Table 18. Evaluation criteria used in value analysis. Measure quantity and basis of criteria are described for each criterion. *from requirements list*

EVALUATION CRITERION	UNIT OF MEASURE	BASIS OF CRITERION*
FLEXIBILITY		
impeller size scope	*weight, diameter & height* limitations of AMT	impeller size scope demands & wishes
material removal capacity	*maximum chip thickness* & *milling capacity*	balance quality grade demands & wishes
fixture & clamping capability	*universality* of fixtures & clamps	automatic workpiece handling, working conditions
key automation ratio	*amount of automated key operations*	functions & working conditions
PERFORMANCE		
lead time	*lead time improvement* for average impeller type with average properties	lead time & production capacity demands
measure uncertainty	*measure uncertainty* of balancing machine (gmm)	balance quality grades, quality demands
machining accuracy	*machining accuracy* of material removal method (mm)	balance quality grades, quality demands
need of preparations for changing impeller type	*amount of preparations* required when changing impeller type	quick setup, working conditions, lead time demands
DURABILITY		
machining tool wear	*rigidity and stability of milling unit*	sufficient machining tool lifetime
wear of rotating components	*extent and accuracy of preventive maintenance plan*	work quality constant, need of maintenance
calibration need	*calibration frequency* & *ease of calibration*	maintenance & quality demands
scope of maintenance	*number of machines* to be preserved in cell	maintenance demands

As table 18 shows, main evaluation criteria for identifying value of specific concept are flexibility, performance and durability. Flexibility describes functional flexibility and ability to adapt to impellers of different design and size while maximizing the level of automation.

Performance describes production efficiency and ability to perform manufacturing stages with high quality. Durability evaluates lifetime and maintenance need of concepts. Moreover, these main criteria are divided into sub-criteria to form more analytical evaluation approach. The following specifications are applied for evaluation criteria:

- Impeller size scope: measured by workpiece weight, diameter and height limitations of machinery. It is a vital criterion of production flexibility because it has direct impact on what sizes of impellers the balancing cell is adaptable with.
- Material removal capacity: measured by maximum chip thickness and milling capability of milling unit. It is directly proportional to the amount of machining runs required for removing specific amount of unbalance which is essential criteria of flexibility, as amount of unbalance grows with impeller size.
- Fixture and clamping capability: measured by universality of fixtures and clamping possibilities. Describes production flexibility as it has big impact on what types and sizes of impellers are reasonable to run through automatic balancing cell by keeping lead time and amount of manual work minimal.
- Key automation ratio: is the ratio of automated key functions and total amount of key functions. Describes functional flexibility of concept. Key functions to be automatized are as follows
    - unbalance correction
    - bur removal
    - diameter trimming
    - moving
    - attaching / detaching
    - data documentation
- Lead time: measured by lead time improvement estimated for average impeller type with average properties. Essential criterion to describe efficiency of production and performance of balancing cell. For average impeller with average properties, lead time of 30 minutes was estimated with existing balancing concept.
- Measure uncertainty: ability to balance near zero unbalance is important, because impeller starts to gather unbalance during pump operation due to wear, damage or deposits (Ruehs 2013, p. 1). Consequently, operational lifetime of impeller is relative

to balancing result, as the closer the impeller is to zero unbalance, the more time it takes for wearing to create operationally harmful unbalance.

- Machining accuracy: measured by machining accuracy of milling unit. Essential criterion of performance, because insufficient machining accuracy may cause bad surface quality, cutting of prohibited areas and inaccurate amount of material to be removed in unbalance correction.
- Need of preparations for changing impeller type: if need of preparations is high and time-consuming, performance of production cell will decrease significantly due to increases in lead time, amount of manual work and risk of manufacturing error.
- Machining tool wear: measured by rigidity and stability of milling unit, as unstable structures can cause excessive vibration to machine tool and significantly decrease tool life. Tool wear issue is highlighted as high strength structural materials are used for impellers. Tool wear is also dependent of tool material and shape, but they are not considered in this study because they are independent of manufacturing concept selection.
- Wear of rotating components: is measured by extent and accuracy of preventive maintenance plan for machinery. If preventive maintenance plan is not specific, it may indicate that OEM or concept supplier does not have proper understanding of maintenance needs and therefore risk of downtime is increased. Wear of rotating components may cause inaccurate unbalance measurements or poor machining quality.
- Calibration need: as measurements are performed and automation is included, ease and frequency of calibration must be considered. Also, complex design and high variation of impeller types may cause challenges in calibration requirements.
- Scope of maintenance: considers the scope of machinery to be preserved. It is simpler and more cost-efficient to preserve minimized number of various machines and systems with differing operational principles.

6.2 Evaluation of manufacturing concepts

Evaluation of manufacturing concept 1 is presented in table 19.

*Table 19. Manufacturing concept 1 grading for value analysis. (Quotation and specifications of supplier 1 2019; Päkki 2019) *for average impeller with average properties*

	CONCEPT 1	**Grade**
FLEXIBILITY		
Impeller size scope	weight limitations: 5–150 kg diameter limitations: 150–625 mm height limitations: ≤ 300 mm → **adaptability to impeller sizes 3-5**	**3**
Material removal capacity	maximum chip thickness: 2,5 mm	**1**
Fixture & clamping capability	manually changeable adapters and clamps for different impeller types and sizes	**1**
Key automation ratio	2 / 6 = 33 %	**1**
PERFORMANCE		
Lead time*	<u>existing concept:</u> 30 min <u>concept 1:</u> 5 min → **25 min improved**	**3**
Measure uncertainty	20 gmm (according to DIN 1319, fixture error not included)	**2**
Machining accuracy	± 20 µm	**2**
Need of preparations for changing impeller type	parameter setup (e.g. balancing parameters, milling spindle speed, feed rate) adapter changing, attaching impeller…	**2**
DURABILITY		
Machine tool wear	Lightweight structure of example construction makes milling process vulnerable to excessive vibration, due to structural materials of impellers with high strength properties	**1**
Wear of rotating components	no preventive maintenance plan due to customized structure	**1**
Calibration need	hard-bearing principle: permanent calibration (self-calibration possible without external help)	**4**
Scope of maintenance	1 key machine: balancing machine with integrated milling unit	**4**

Arguments of manufacturing concept 1 grading:

- Impeller size scope: weight, diameter and height limitations of workpiece restrict concept 1 adaptability to impeller sizes 3-5, although some impellers from other categories could also be processed with concept 1 according to impeller property variations (table 5).
- Material removal capacity: by using correction area calculations presented in appendix 3, removing average amount of unbalance from average impeller would require cut depth of 2,65 mm, which means that in a similar case concept 1 would

have to perform two machining runs due to its maximum cutting depth of 2,5 mm. This would lead to increased lead times of average impellers to be balanced, which gives a low grade for concept 1.

- Fixture and clamping capability: concept 1 utilizes manually changeable adapters and clamps for different kind of impellers due to challenges in automatization. Low grade is given due to amount of manual work caused to operator while the aim was to find fully automatic concepts.
- Key automation ratio: automatized key functions are correction and documenting results.
- Lead time: concept 1 lead time for balancing is estimated to be 5 minutes taking into consideration work stages illustrated in operation flow chart (figure 16). Unbalance measuring is estimated to take maximum 30 seconds. For unbalance correction via milling, maximum chip thickness is 2,5 mm, which means that average balancing case would require only one machining run that is estimated to take maximum 2 minutes. About 2,5 minutes is estimated for moving, attaching and detaching impeller, which makes total estimated lead time 5 minutes.
- Measure uncertainty: specified 20 gmm according to DIN 1319 without considering fixture error.
- Machining accuracy: specified ± 20 µm.
- Need of preparations for changing impeller type: changing impeller type requires parameter setup (e.g. balancing parameters, milling spindle speed, feed rate), adapter changing and manual detaching and attaching.
- Machine tool wear: lightweight structure of example construction makes milling process vulnerable to excessive vibration, due to structural materials of impellers with high strength properties.
- Wear of rotating components: no preventive maintenance plan was available during the study due to customized structural solutions in concept 1, so low grade was given.
- Calibration need: hard-bearing balancing machine provides permanent calibration which means that calibration is not required when changing impeller types. Calibration must still be performed in specific time periods.
- Scope of maintenance: simple and compact cell layout with only one machine to be preserved.

Evaluation of manufacturing concept 2 is presented in table 20.

Table 20. Manufacturing concept 2 grading for value analysis. (Quotation and specifications of supplier 2 2019.)

	CONCEPT 2	**Grade**
FLEXIBILITY		
Impeller size scope	weight limitations: 20-400 kg diameter limitations: ≤ 850 mm height limitations: ≤ 450 mm → **adaptability to impeller sizes 4-6**	**2**
Material removal capacity	maximum chip thickness not available, due to modification requirements of milling unit	**1**
Fixture & clamping capability	manual changing of adapters and clamps	**1**
Key automation ratio	2 / 6 = 33 %	**1**
PERFORMANCE		
Lead time	<u>existing concept:</u> 30 min <u>concept 2:</u> 10 min → **20 min improved**	**2**
Measure uncertainty*	5-10 gmm (according to ISO 2953)	**4**
Machining accuracy	not available	**1**
Need of preparations for changing impeller type	loading impeller to balancing machine, manual changing of adapter and tooling, parameter setting	**2**
DURABILITY		
Machine tool wear	Unstable example structure of milling unit can cause excessive vibration during milling, due to structural materials of impellers with high strength properties	**1**
Wear of rotating components	no preventive maintenance plan due to customized structure	**1**
Calibration need	hard-bearing principle: permanent calibration (self-calibration possible without external help)	**4**
Scope of maintenance	2 key machines: balancing machine, CNC milling unit	**3**

Arguments of manufacturing concept 2 grading:

- Impeller size scope: weight, diameter and height limitations of workpiece restrict concept 2 adaptability to impeller sizes 4-6, although some impellers from other categories could also be processed according to impeller property variations (table 5). Concept 2 gets lower grade than concept 1, as adaptability to 1-3 sizes is prioritized over 6-7 sizes.

- Material removal capacity: no estimations were available for maximum chip thickness due to modification requirements of milling unit. Therefore, unreliability of material removal capacity gives a low grade.
- Fixture and clamping capability: concept 2 requires manual changing of adapters and clamps. Low grade is given due to amount of manual work caused to operator while the aim was to find fully automatic concepts.
- Key automation ratio: automatized key functions are correction and documenting results.
- Lead time: concept 2 lead time is estimated to be 10 minutes taking into consideration all stages. Unbalance measuring and correction are estimated to last 60–70 seconds excluding manual work; moving, attaching, detaching and turning impeller upside down for unbalance correction (Quotation and specifications of supplier 2 2019, p. 12).
- Measure uncertainty: specified 5-10 gmm for single-plane balancing according to ISO 2953.
- Machining accuracy: not available. Therefore, low grade is given for unreliability.
- Need of preparations for changing impeller type: changing impeller type requires parameter setup, adapter changing, manual detaching and attaching and tooling changeover. Tooling changeover time is approximated 6 minutes (Quotation and Specifications of supplier 2 2019, p. 7).
- Machine tool wear: unstable example structure of milling unit can cause excessive vibration during milling, due to structural materials of impellers with high strength properties.
- Wear of rotating components: no preventive maintenance plan was available during the study due to customized structural solutions in concept 2, so low grade was given.
- Calibration need: hard-bearing balancing machine provides permanent calibration which means that calibration is not required when changing impeller types. Calibration must still be performed in specific time periods.
- Scope of maintenance: simple and compact cell layout with two machines to be preserved.

Evaluation of manufacturing concept 3 is presented in table 21.

*Table 21. Manufacturing concept 3 grading for value analysis. (Quotation and specifications of supplier 3 2019.) *See arguments below table 21.*

	CONCEPT 3	**Grade**
FLEXIBILITY		
Impeller size scope	1. balancing machine: weight limitations: 10-300 kg (incl. adapter and clamping tool) diameter limitations: ≤ 810 mm height limitations: ≤ 450 mm 2. vertical lathe: weight limitations: ≤ 500 kg (incl. chuck) diameter limitations: ≤ 760 mm height limitations: ≤ 770 mm 3. robot manipulator: weight limitations: ≤ 165 kg → **adaptability to impeller sizes 3-6***	**4**
Material removal capacity	maximum chip thickness not available, but expected to be significantly improved in comparison to other concepts*	**5**
Fixture & clamping capability	automatic clamp changing, universal adapter attached to all impeller types fitting every machine in cell	**5**
Key automation ratio	5 / 6 = 83 %	**4**
PERFORMANCE		
Lead time	**1. balancing:** existing concept: 30 min concept 3: 5 min **2. diameter trimming:** 10-15 min improvement to existing concept	**5**
Measure uncertainty	single-plane: 10-25 gmm	**3**
Machining accuracy	± 4 µm	**5**
Need of preparations for changing impeller type	manual attaching of universal adapter to impeller, parameter setup	**4**
DURABILITY		
Machine tool wear	large construction with rigid column structure made specifically for heavy milling → minimized vibration to milling tool	**5**
Wear of rotating components	extensive and specific preventive maintenance plan of OEM available	**5**
Calibration need	hard-bearing principle: permanent calibration (self-calibration possible without external help)	**4**
Scope of maintenance	3 key machines: two vertical turning lathes and balancing machine	**2**

Arguments of manufacturing concept 3 grading:

- Impeller size scope: concept 3 adaptability covers sizes 3–6, although portion of lightest impellers in size 3 may not be adaptable due to balancing machine weight limitations.

- Material removal capacity: no estimations were available for maximum chip thickness, but vertical turning lathe is specifically designed for heavy milling with state-of-the-art features. Therefore, it can be expected that material removal capacity is supreme to other manufacturing concepts.
- Fixture and clamping capability: relatively high for concept 3. Universal adapter compatible with all machinery would be attached to impeller before robot manipulator grabs and enters it to manufacturing cell. This universal solution would allow robot manipulator to attach impeller automatically to every machine in cell. Although, it should be considered carefully if this kind of adapter can be manufactured accurately enough, so that unbalance measurement accuracy and machining accuracy do not suffer excessively. In comparison to concepts 1 and 2, concept 3 capability for fixing and clamping is significantly improved.
- Key automation ratio: automatized key functions are correction, diameter trimming, moving, attaching / detaching and documenting results.
- Lead time: concept 3 lead time is estimated to be 5 minutes for balancing. Additionally, concept 3 provides estimated improvement of 10–15 minutes to diameter trimming, which gives a higher grade in comparison to other concepts. Diameter trimming improvement is achieved mostly due to combined cell layout and automatic clamping & fixing. Actual trimming time may also be shortened.
- Measure uncertainty: specified 10–25 gmm.
- Machining accuracy: specified ± 4 µm.
- Need of preparations for changing impeller type: changing impeller type requires manual attaching of universal adapter to impeller and parameter setup.
- Machine tool wear: large construction with rigid column structure made specifically for heavy milling and state-of-the-art process optimization software minimizes vibration to milling tool (Quotation and Specifications of supplier 3 2019).
- Wear of rotating components: OEM provides a specific preventive maintenance checklist to minimize downtime of vertical turning lathe, which gives significantly higher grade in comparison to other concepts that lack maintenance plans. Main reason for this is that concept 3 allows to use nearly standard machinery with known properties for material removal. In concepts 1 and 2, more customized milling units must be utilized, which is why preventive maintenance needs are harder to estimate and downtime is likely increased.

- Calibration need: hard-bearing balancing machine provides permanent calibration which means that calibration is not required when changing impeller types. Calibration must still be performed in specific time periods.
- Scope of maintenance: complexity of cell layout with balancing machine and two vertical turning lathes to be preserved gives lower grade than for other concepts.

6.3 Results of value analysis

Geometric averages of sub-criteria are calculated to form grades of main criteria that are flexibility, performance and durability. Table 22 summarizes given grades and shows geometric averages (GA) of main criteria for each concept.

*Table 22. Geometric averages (GA) for flexibility, performance and durability based on given grades for sub-criteria. *for changing impeller type*

	CONCEPT 1	**CONCEPT 2**	**CONCEPT 3**
Impeller size scope	3	2	4
Material removal capacity	1	1	5
Fixture & clamping capability	1	1	5
Key automation ratio	1	1	4
FLEXIBILITY, GA	**1,32**	**1,19**	**4,47**
Lead time	3	2	5
Measure uncertainty	2	4	3
Machining accuracy	2	1	5
Need of preparations*	2	2	4
PERFORMANCE, GA	**2,21**	**2,00**	**4,16**
Machine tool wear	1	1	5
Wear of rotating components	1	1	5
Calibration need	4	4	4
Scope of maintenance	4	3	2
DURABILITY, GA	**2,00**	**1,86**	**3,76**

As table 22 shows, concept 3 received highest grades in flexibility, performance and durability with significant difference to concepts 1 and 2. Concepts 1 and 2 are close to each other in every main criterion. GA's of main criteria are then multiplied by given weight factors that were identified for each main criterion with pairwise comparison. Table 23 shows weighted grading for each concept.

Table 23. Weighted grading of value analysis. Sums of weighted grades gives ranking for concepts based on key properties. GA = geometric average, W = weight factor.

	CONCEPT 1	**CONCEPT 2**	**CONCEPT 3**
Flexibility (W · GA)	6,58	5,95	22,36
Performance (W · GA)	6,64	6,00	12,49
Durability (W · GA)	2,00	1,86	3,76
Property points = ∑ (W · GA)	**15,2**	**13,8**	**38,6**

As table 23 shows, concept 3 has the most suitable properties for automatization of balancing by receiving over two times higher grade than concept 1 and almost three times higher grade than concept 2. RC's of concepts are illustrated in table 24.

Table 24. Relative costs (RC) of concepts. Cost of concept 1 is used as a reference cost.

	CONCEPT 1	**CONCEPT 2**	**CONCEPT 3**
Relative cost (RC)	1,00	1,14	3,14

Cost of concept 3 is approximately three times higher than cost of concept 1 and 2, as shown in table 24. Points given for properties are finally divided with relative costs (RC) to obtain values of concepts. Values of concepts are shown in table 25.

Table 25. Values of concepts. Values are obtained by dividing property points with relative costs. RC = relative cost.

	CONCEPT 1	**CONCEPT 2**	**CONCEPT 3**
Value = [∑ (W · GA)] / RC	15,2 points / €	12,1 points / €	12,3 points / €

When considering relative costs, concept 1 receives the highest grading and proves to be the most valuable concept based on points per cost as seen from table 25. Even though concept 3 was ranked the most suitable solution in terms of property points representing essential properties, its high relative cost reduces concept value significantly. Values of concepts are adjusted to relative risk levels of concepts ultimately.

7 RISK ANALYSIS OF MANUFACTURING CONCEPTS FOR AUTOMATIZATION OF IMPELLER BALANCING

Goal of this study was to provide the most value adding manufacturing concept for automatization of impeller balancing. Decision for further development and proceeding with the investment of the most valuable concept will be given based on results of this study. Thus, it is essential that risks of each concept are examined comprehensively before making decisions. To fulfill this necessity, risk analysis consisting of risk assessment and risk management is conducted for each concept and values of concepts obtained from value analysis will be adjusted to relative risk levels.

7.1 Recognizing risks related to advanced manufacturing technology investments

As García & Alvarado state in their study, investing in advanced manufacturing technology (AMT) can lead to major benefits but also to significant losses if the implementation process is not managed in a proper way. (García & Alvarado 2012, p. 123.) García & Alvarado (2012, p.130) were able to identify a total of eight main factors representing almost 75 % of the problems in implementation of AMT for manufacturing companies located in Mexico:

- installation and setup
- maintenance
- supplier relationships
- investment justification process
- decision and analysis process
- lack of knowledge
- custom
- failures and differences with the ordered AMT

(García & Alvarado 2012, p. 130.)

All mentioned factors above could be possible problem areas of implementation of manufacturing concept to automatize impeller balancing. It should be remembered that implementation problems are still dependent on different factors, such as industry, geographical location or financial situation of company. Furthermore, a scientific review of AMT's effectiveness states that 50–75 % of AMT adoptions fail somehow. Lack of knowledge in AMTs causes implementation issues related to system flexibility. It is stated that also cultural change is often required when implementing AMTs and may not be easy if company management is not open-minded for cultural changes. (Goyal & Grover 2012, p. 256.)

Justification of AMT systems has proven to be challenging as well. Traditional financial evaluation methods are not appropriate alone, as AMTs provide both tangible and intangible benefits. This may lead to a situation where managers are forced to reject investment to AMT that would be beneficial to the company. Goyal and Grover state that main obstacle in adopting AMT is the lack of suitable justification methods. (Goyal & Grover 2012, p. 256.) Thus, AMT justification should include proper measures of tangible and intangible aspects.

Additionally, Goyal and Grover reviewed a study stating that different implementation strategies should be used depending on AMT adoption time of company. Early adopters for AMT are given a recommendation to focus on learning from vendors and experts who clarify uncertainties in the production process. Recommendation to compare different equipment combinations instead of comparing different process technology is given for late AMT adopters. Early and late adopter firms were categorized based on the corresponding technology level of their direct competitors. Recommendations differ since late adopters have lower risk regarding process uncertainty as they benefit from possibility to observe early adopters. (Goyal & Grover 2012, p. 259.) Acquiring AMT is typically significant financial investment, while minority succeed in utilizing AMT's due to the multi-stage implementation process. (Goyal & Grover 2012, p. 258.) In conclusion, investing in AMT solutions as early adopter contains significant risks that should be considered before making decisions. During data collection phase, discussions with experts, suppliers and manufacturers of impeller balancers and AMT solutions indicated that target company of this study belongs to early adopters as similar kind of projects had not been implemented. Therefore, research methodology and approaches utilized to form three different manufacturing concepts were appropriate.

7.2 Risk analysis of manufacturing concepts

The most significant risks related to automatization of impeller balancing are identified and possible consequences and risk management methods are presented in table 26.

Table 26. Risk assessment, expected consequences and risk management. PD = production development department of target company, O = cell operator of target company, S = concept supplier or OEM.

RISK ASSESMENT	POSSIBLE CONSEQUENCES	RISK MANAGEMENT	RESPONSIBLE FOR MANAGING
Operational			
bad usability	• increased lead time	• training operator • clear interface requirements to supplier	PD / O
serious machine malfunction	• increased downtime	• preventive maintenance • keep one manual balancing cell in operation	PD / S
reduced impeller scope	• reduced utilization rate → increased payback time	• inform supplier of lacking properties • keep one manual balancing cell in operation	S / PD
Technical			
short technological lifecycle	• reduced competitive advantage • reduced value of investment	• compare latest technology	PD
bad surface quality / bur on surface	• manual grinding required	• adjust & optimize milling program • ensure no vibration sources nearby	PD / O
malfunction in algorithm	• increased lead time • quality issues	• acceptance test for created algorithms	PD / S
Durability			
plastic deformation of structures	• increased measure uncertainty → unbalanced impellers installed to pumps • bad surface quality • machining tool break	• ensure no excessive vibration sources nearby • select stricter balance quality grade G	PD / S
performance affected by excessive vibration	• increased measure uncertainty • limited correction speed → increased lead time	• proper foundation • ensure no vibration source nearby • increase damping properties in design	S / PD
Supplier			
lack of maintenance support	• increased downtime	• sign binding maintenance contract • preventive maintenance	S / PD
Implementation			
unexpected issues in implementation	• increased investment costs • delayed implementation	• detailed implementation plan	PD / S

Risk analysis focuses on determining severity and probability of risks identified in table 26. Numerical values of probabilities or severities were not utilized due to reliability issues in estimating correct values. For example, cost of downtime could be calculated reliably but amount of downtime caused by each risk would be highly unreliable estimation if given. Therefore, qualitative approach was chosen as more reliable method to conduct comparative risk analysis for manufacturing concepts.

7.2.1 Arguments of risk priority classifications

Risk priority classes (RPC) are determined for each risk in each manufacturing concept. RPC's are determined by comparing severities and probabilities of risks between concepts. Arguments for RPC's are presented as follows:

Operational:

- Bad usability has highest probability in concept 2, as it includes two different machines and does not provide any key automated functions than correction and documenting results. Concept 1 probability is lowest due to simplest cell concept. Concept 3 is the most flexible to adjust usability although it may prove to be challenging in detailed design phase, but severity is the highest as several different functions and machines are integrated together.
- Serious machine malfunction has the biggest impact in concept 3 due to amount of affected machinery and functions. All functions are synchronized in concept 3, so malfunction in one function causes problems in all the other functions. Concept 2 malfunction is not as severe as concept 1, because separate measuring and correction machines are used in concept 2 and their functions do not depend on each other.

Technical:

- Short technological lifecycle is the most probable in concept 1 and least probable in concept 3 due to its flexibility in functions. On the other hand, severity is highest for concept 3 due to highest relative cost and large amount of resources required in implementation and installation. Technological lifecycle has significant influence on long-term competitive advantage of target company.
- Bad surface quality / bur on surface is the most probable in concept 1 due to relatively unstable structure of machinery when compared to concepts 2 and 3. Concept 1 balancing machine structure with integrated milling unit structure is not as robust structural solution as in other concepts.

- Malfunction in algorithm is the most probable in concept 3 as it includes the most programming and has the most functions that must be synchronized together. Severity is also highest in concept 3 due to number of synchronized functions.

Durability:

- Plastic deformation of structure is the most probable for concept 1 due to relatively unstable structure in comparison to other concepts. Severity for all concepts is extreme as operational reliability of measuring and machining suffer equally.
- Performance affected by excessive vibration is most likely for concept 1 due to relatively unstable structure in comparison to other concepts. Robust machine structures and utilized technical solutions of concept 3 provide improved damping properties, which is why probability for concept 3 is the lowest.

Supplier:

- Lack of maintenance support is most probable in concept 2, as there is no Finnish importer like in other concepts and concept 2 would likely be one of a kind in Finland. Therefore, lack of maintenance support is expected.

Implementation:

- Unexpected issues in implementation are highly probable in concepts 1 and 2 and expected for concept 3. Severity is also increased for concept 3 due to relatively large size of concept that requires the most preparations in implementation.

7.2.2 Relative risk levels of manufacturing concepts

Based on risk priority arguments, identified risks are placed in risk matrix according to probability and severity. RPN’s are calculated based on RPC’s. Table 27 illustrates risk matrix of manufacturing concept 1.

Table 27. Risk matrix of manufacturing concept 1. Areas with different colors represent different RPC's. Red = prevent, orange = minimize, yellow = consider if need to minimize, green = tolerate.

Concept 1		**Probability**				
		Not likely	Low	Moderate	High	Expected
Severity	Insignificant					
	Low		**Bad usability**		**Unexpected issues in implementation**	
	Moderate			**Bad surface quality or bur on surface**	**Reduced impeller scope**	
	High		**Malfunction in algorithm**	**Lack of maintenance support / Performance affected by excessive vibration**	**Short technological lifetime**	
	Extreme		**Serious machine malfunction**	**Plastic deformation of structures**		

As table 27 illustrates, majority of identified risks are accumulated on orange and red areas, which means that they should be prevented or minimized in manufacturing concept 1. Table 28 shows calculation of RPN for concept 1.

Table 28. RPN calculations of manufacturing concept 1. Higher RPN represents higher priority of risks. Maximum RPN = 100.

RPC	Priority weight	No. of risks	RPN
Red	10	2	20
Orange	7	7	49
Yellow	4	1	4
Green	1	0	0
TOTAL RPN			**73**

As table 28 states, total RPN of 73 is obtained for manufacturing concept 1. RPN is ultimately compared to RPN's of other concepts to make conclusions. Table 29 shows risk matrix for manufacturing concept 2.

Table 29. Risk matrix of manufacturing concept 2. Areas with different colors represent different RPC's. Red = prevent, orange = minimize, yellow = consider if need to minimize, green = tolerate.

Concept 2		Probability				
		Not likely	Low	Moderate	High	Expected
Severity	Insignificant					
	Low				Unexpected issues in implementation	
	Moderate	Bad surface quality or bur on surface	Reduced impeller scope	Short technological lifecycle	Bad usability	
	High		Malfunction in algorithm / Performance affected by excessive vibration	Serious machine malfunction		Lack of maintenance support
	Extreme		Plastic deformation of structures			

As table 29 shows, most of the identified risks are accumulated to orange and red areas, which means that they should be prevented or minimized in manufacturing concept 2. Bad surface quality is not likely to occur, which classifies it as tolerable risk. Table 30 shows calculation of RPN for concept 2.

Table 30. RPN calculations of manufacturing concept 2. Higher RPN represents higher priority of risks. Maximum RPN = 100.

RPC	Priority weight	No. of risks	RPN
Red	10	1	10
Orange	7	7	49
Yellow	4	1	4
Green	1	1	1
TOTAL RPN			**64**

As table 30 shows, total RPN of 64 is obtained for manufacturing concept 2. RPN is ultimately compared to RPN's of other concepts to make conclusions. Table 31 shows risk matrix for manufacturing concept 3.

Table 31. Risk matrix of manufacturing concept 3. Areas with different colors represent different RPC's. RED = prevent, ORANGE = minimize, YELLOW = consider if need to minimize, GREEN = tolerate.

Concept 3		Probability				
		Not likely	Low	Moderate	High	Expected
Severity	Insignificant					
	Low					
	Moderate	Bad surface quality or bur on surface	Lack of maintenance support			Unexpected issues in implementation
	High	Performance affected by excessive vibration	Bad usability	Malfunction in algorithm		
	Extreme	Reduced impeller scope	Plastic deformation of structures / Short technological lifetime	Serious machine malfunction		

As table 31 states, risks are accumulated on different RPC areas. Six of the identified risks should be prevented or minimized, while three of the risks are classified as tolerable. Need to minimize the risk of lacking maintenance support should be considered. Table 32 shows calculation of RPN for concept 3.

Table 32. RPN calculations of manufacturing concept 3. Higher RPN represents higher priority of risks. Maximum RPN = 100.

RPC	Priority weight	No. of risks	RPN
Red	10	2	20
Orange	7	4	28
Yellow	4	1	4
Green	1	3	3
TOTAL RPN			**55**

As table 32 shows, total RPN of 55 is obtained for manufacturing concept 3. RPN's of all manufacturing concepts are summarized in table 33. Additionally, relative risk level and amount of risk reduction are illustrated.

Table 33. Comparison of RPN, relative risk level and risk reduction of manufacturing concepts.

	Concept 1	**Concept 2**	**Concept 3**
RPN	73	64	55
Relative risk level	reference	88 %	75 %
Risk reduction	reference	- 12 %	- 25 %

As table 33 shows, manufacturing concept 1 has highest priority of risk. Relative risk levels and risk reductions are ratios of RPN's. Concept 2 includes 12 % smaller risk than concept 1, while concept 3 includes 25 % smaller risk in comparison to concept 1.

8 INVESTMENT RECOMMENDATION, JUSTIFICATION AND IMPLEMENTATION PLAN

As studies have stated, justification for AMT investments is challenging. Traditional financial determinants, such as payback time or return of investment (ROI) are identified as inappropriate determinants as they do not consider the overall benefits of implementing AMT that include tangible and intangible aspects. It is stated that strategical determinants are essential to utilize in addition to financial ones. (Goyal & Grover 2012, p. 261.) Therefore, in addition to direct financial effects of investment, intangible and strategical aspects are examined for the recommended concept.

8.1 Investment recommendation based on relation of value and risk

Recommendation of the most suitable manufacturing concept for automatization of impeller balancing is based on values and relative risk levels. Table 34 summarizes results of value and risk analysis for manufacturing concepts.

Table 34. Values and relative risk levels of manufacturing concepts.

	Concept 1	**Concept 2**	**Concept 3**
Value	15,2 points / €	12,1 points / €	12,3 points / €
Relative risk level	100 %	88 %	75 %
Risk reduction	reference	- 12 %	- 25 %

Values of concepts are then adjusted to relative risk levels. Table 35 shows relation of value and risk for manufacturing concepts.

Table 35. Values of manufacturing concepts divided with relative risk levels.

	Concept 1	**Concept 2**	**Concept 3**
Value / Relative risk level	15,2 points / €	13,8 points / €	16,3 points / €

As table 35 shows, concept 3 provides the most value when adjusted to relative risk level. Therefore, a recommendation to select manufacturing concept 3 for automatization of impeller balancing is given. Additional recommendation to keep at least one manual balancing cell and diameter trimming cell functioning is given, as there exists significant amount of uncertainty in implementation and operation of automatic balancing cell.

8.2 Direct financial effects of investment

The purpose of financial calculations presented in this study is to demonstrate the potential of successfully implementing manufacturing concept 3 to automatize impeller balancing and diameter trimming. It should be noted that cost allocations and given values do not represent true numbers and are estimations of the researcher to give an example of achievable financial benefits in balancing and diameter trimming. All values should be recalculated in order to get reliable estimations of financial effects. The following is an example of how financial benefits could be calculated:

- Existing concept cost allocations and lead time in impeller balancing and diameter trimming: (not representing any true numbers)

  balancing operator = 50 € / h
  machinist = 50 € / h
  manual lathe = 100 € / h
  balancing station = 75 € / h
  lead time of average impeller = 0,5 h (balancing) + 1 h (diameter trimming)
  cost of balancing and trimming of average impeller =
  1,5 h · (50 + 50 + 100 + 75) € / h = 413 € / impeller

- Concept 3 cost allocations and lead time: (not representing any true numbers)

  operator of balancing and diameter trimming cell = 50 € / h
  machinery = 300 € / h
  lead time of average impeller = 5 min (balancing) + 50 min (trimming)
  cost of balancing and trimming of average impeller =
  (1/12 + 5/6) h · (50+300) € / h = 321 € / impeller

Furthermore, cost savings are dependent on production rate and could be calculated as follows: (not representing any true numbers)

- 1000 impellers / year · (413 – 321) € / impeller = 91 667 € / year
- 1500 impellers / year · (413 – 321) € / impeller = 137 500 € / year
- 2000 impellers / year · (413 – 321) € / impeller = 183 333 € / year

Calculations of financial measures such as payback time and ROI are not included in this study, as they would indicate classified information about investment costs of manufacturing concept 3.

8.3 Intangible effects of investment

As stated previously, intangible effects of AMT investments such as manufacturing concept 3, should be accounted in justification of investment. The most influential intangible justification arguments derived from analyses for concept 3 are following:

- Flexibility of production: utilizing vertical lathes gives possibility for diameter trimming of impellers. This means that balancing and diameter trimming can be integrated to same cell and need of operators reduces from two to one. Additionally, concept 3 could be adaptable for impeller shape machining in the same cell and thus these three machining stages of impellers could be handled automatically in same cell by one operator. Integrating pre-machining stage of impellers to same cell would likely be challenging, because impeller castings include at least some level of dimensional errors, which lead to challenges in centering impeller from its hub (Ratia 2019).
- Reliability of operational principles: the most common structural materials of cast components of pumps at target company are austenitic-ferritic duplex steels. Austenitic stainless steels are considered to have relatively poor machinability because of their high work hardening rate, tensile strength and fracture toughness as an example (Paro, Hänninen & Kauppinen 2001, p. 279). Proposed vertical lathes of manufacturing concept 3 are specifically designed for heavy-duty milling and turning. They can also be utilized with small or no modifications at all to standard structure, which is not the case with concepts 1 and 2 where milling units must be customized to fit the requirements. Separate unbalance measuring and machining stations ensure that these operations do not affect negatively to each other for example by creating harmful vibration to measuring spindle during machining.

- Production performance and lead time: with the best machining accuracy, machining capability and possibility to combine several manufacturing stages to one automated cell, production performance and lead time outplay concepts 1 and 2. In comparison to existing concept at target company, effect of employee's performance to impeller quality and lead time would be eliminated.
- Competitive advantage gained from AMT included in concept 3: if implementation of AMT in concept 3 is successful, significant productivity boost could be obtained. This would lead to reduced production costs and improvements in lead time. Therefore, successful implementation of concept 3 could lead to increased competitive advantage in comparison to industry competitors.
- Significantly improved working conditions: as presented in pre-comparison, concept 3 would not cause any direct contact to hazardous materials. Operator would not have to wear any additional safety equipment in addition to factory's standard safety equipment. No heavy manual grinding requiring extreme precision due to strict quality demands in unbalance correction is required, which would likely improve quality of impellers in terms of better surface quality and improved hydraulic performance. Additionally, it could lead to reduction in sick leaves due to minimized risk of physical injuries. Automatic correction, automatic documentation of balancing results and improvement in air quality were also the most desired properties when asking about improvement needs in current balancing concept (Semi-structured interviews 2019).
- Improvements in impeller quality: as manual manufacturing stages could be removed totally with concept 3, manufacturing error caused by human operator would be minimized. Although, it should be remembered that with automatic systems, the effect of small mistake can be extreme in some scenarios and result in several flawed impellers if system is not observed. Still, risk of this kind of cumulating error would exist only if production cell is left unobserved. Additionally, reduced measure uncertainty, more robust foundation and state-of-the-art technology in comparison to existing machinery would ensure that impellers will be closer to zero unbalance and thus impeller lifetime and pump performance could be improved.

While concept 3 could provide significant intangible benefits, the importance of detailed design phase must be accounted for successful concept design and implementation. When combining high level of automation with highly specific manufacturing stages, the detailed design phase may take significant amount of resources from target company and supplier. The most significant aspects to be considered in the detailed design phase for concept 3 are as follows:

- Identification of permissible material removal area in unbalance correction
- Generating optimized machining tool path for correction milling
- Considering the effect of dimensional errors in impeller castings
- Synchronization of every machine to function fluently together, data management and transportation from one machine to another
- Universal fixture adapter design: what are the required dimensional and shape tolerances for adapter to keep sufficient accuracy in unbalance measuring, unbalance correction milling and diameter trimming
- Optimal workflow inside automated cell
- Examining other factors affecting productivity of the cell

Aspects above should be accounted in detailed design phase thoroughly. It can be expected that significant work input is required from target company and concept supplier to find suitable solutions for the mentioned aspects.

8.4 Implementation plan and timetable

Proposed implementation plan and timetable apply in a situation, where target company has assigned a dedicated project group for planning and implementation of investment. Management must also be in close cooperation with the project group to ensure successful implementation. Investment plan consists of the following phases:

1. Negotiations with supplier on how to proceed with the investment
    - Proposing the detailed design and implementation plan and considering comments from supplier
2. Detailed design phase (6 months)
    - AMT concept requires significant amount of work in detailed design phase; the most challenging field being automation and integrating different machinery to function properly together
3. Concept testing (1-2 months)

- Critical functions must be tested in practice with different impeller types to ensure flawless operation

4. Review of test results and further testing (1-2 months)
   - Adjusting production parameters to improve productivity
   - Simulating different work flows to find the most productive operation sequence
   - Adjusting cell layout to the best work flow
5. Decision to implement
6. Arrangements at the factory (1 month)
   - Space must be arranged for new AMT balancing cell
   - Balancing cell 2 must be modified so that impeller sizes 1-7 can be balanced there. It involves moving two balancing machines to the cell and modifying air conditioning system. Machine foundations must be done properly.
7. Delivery of machinery (delivery time from placing order)
8. Installation, implementation and training of staff (1 months)

In the longest scenario, it would take one year from the beginning of detailed design phase to start-up of new balancing cell. In the shortest scenario, it would take 10 months until the start-up. Timetable should be observed with certain criticism as detailed design phase depends a lot on available resources. A recommendation to keep at least one manual balancing cell and diameter trimming cell functioning is given as there exists significant amount of uncertainty in implementation and operation of automatic balancing cell.

9 DISCUSSION

Comparison between three potential manufacturing concepts for automatization of impeller balancing was based on multi-attribute decision-making (MADM) system that consisted of value analysis and risk analysis. Ultimately, results of value analysis were adjusted to results of risk analysis to justify selection of the most suitable manufacturing concept.

Evaluation criteria for value analysis were derived from requirements list that was approved by development manager of target company. Property points were given in value analysis according to how well a manufacturing concept could respond to evaluation criteria. Property points were then divided by relative investment costs to obtain values for each concept. The main purpose of value analysis was to recognize, which of the concepts provides most value for target company and to identify strengths and weaknesses in the key fields of flexibility, performance and durability.

As stated in the beginning of risk analysis, AMT investments include significant risks specifically in implementation. Furthermore, a scientific review of AMT's effectiveness stated that 50-75 % of AMT adoptions fail somehow. (Goyal & Grover 2012, p. 256.) Therefore, adjusting value obtained from value analysis to relative risk levels obtained from risk analysis was required. At first, the most significant risks related to automatization of impeller balancing, their possible consequences and ways to manage them were identified. Identified risks were then placed in risk matrix based on probability and severity for each concept to obtain risk priority classes (RPC). Based on RPC's, risk priority numbers (RPN) were calculated and finally relative risk levels were obtained by comparing RPN's between each concept.

Recommendation of the most suitable manufacturing concept for automatization of impeller balancing was given based on relation of value and relative risk level. Therefore, key properties, investment costs and the most significant risks were considered in evaluation and selection process to form a solid justification for selected manufacturing concept.

Financial measures, such as payback time and ROI were not presented in this study as they would reveal classified information about investment costs. Nevertheless, an example to calculate cost savings caused by reduction of needed employees and shortened lead time was given. Estimated costs were not based on true values but gave a perspective of the potential of selected manufacturing concept. Additionally, intangible aspects were included in justification. To identify cost effects of presented intangible aspects, further study would be required.

After justification of investment, implementation plan with timetable was drafted for the recommended manufacturing concept. With implementation plan included in the study, a view of requirements for investing in new concept was given for target company. In conclusion, study provided wide-range analysis including evaluating, selecting, justifying and planning implementation of a new manufacturing concept for automatization of impeller balancing.

9.1 Key findings of the study

Manufacturing concept 3 including balancing machine, two vertical lathes and robot manipulator proved to be the most valuable concept with 16,3 points / € after adjusting value with relative risk level, while concept 1 received 15,2 points / € and concept 2 got 13,8 points / €. When observing the results of value analysis without adjusting results to relative risk levels, concept 1 would have proved to be the most valuable concept. This emphasizes the significance of relative risk levels considered in evaluating values of concepts, as without risk analysis concept 1 would have seemed as the most valuable concept and significant risks would not have been recognized. When observing results of value analysis before dividing property points with relative costs, concept 3 would have won the comparison with over two times higher points than second best concept. Thus, capability of concept 3 to respond property requirements would be best, while this also emphasizes the significance of including financial aspects as well as risk levels in comparison. Otherwise selection would have been based solely on technical properties without knowledge of cost effects or risks.

The most significant benefits of manufacturing concept 3 in comparison to concepts 1, 2 and existing balancing concept at target company are as follows:

- Production flexibility: integrating balancing and diameter trimming to same cell enables one operator to handle both manufacturing stages and enables additional reductions in lead time.
- Options to extend functionality: with state-of-the-art vertical lathes the possibilities of integrating impeller shape machining to same cell should be further examined, as it could boost productivity of the cell significantly.
- Operational reliability: with separate machines for each manufacturing stage and utilization of standard machines without need of modifications, operational reliability is improved in comparison to all other concepts.
- High level of automation: eliminates disadvantages of existing balancing concept more efficiently than concepts 1 or 2. With the level of automation provided, occupational safety is significantly improved while lead time and impeller quality are not dependent of employee’s performance in challenging conditions.
- Competitive advantage: if successfully implemented, concept 3 could provide competitive advantage, as background study indicated that similar kind of automation systems are still rare for applications such as impeller balancing.

Furthermore, vertical lathes of concept 3 utilize cutting-edge energy-saving technology, while similar features were not found for concepts 1 and 2. This means that concept 3 provides additional features to minimize energy consumption which was defined as a wish in requirements list.

The most significant disadvantages of manufacturing concept 3 in comparison to concepts 1, 2 and existing balancing concept at target company are as follows:

- Complexity of manufacturing concept: as several different machines and functions must be synchronized together to enable the level of automation presented, importance of the detailed design phase is highlighted in terms of operational reliability and productivity.
- Risks related to machine malfunction, usability and implementation: if one of the machines in concept 3 stops operating, it would likely stop operation of the whole cell. Likewise, if any kind of manufacturing error happens during operation and it is not accounted properly, it may lead to errors in every function of concept 3. Due to complexity of concept, also implementation and usability include considerable risks.

- High investment costs possibly requiring higher production rate: as relative cost of concept 3 is approximately three times higher than relative cost of concept 1 and 2, higher production rate of impellers may be required to justify investment in traditional financial measures, such as payback time or ROI.

9.2 Practical test to verify operation of automatic unbalance correction

To verify that selected unbalance correction principle by milling works in practice, a practical test was implemented. Large variation of complex impeller designs and dimensions creates challenges in automatization of unbalance correction, as automatic correction requires NC code that identifies the allowable material removal area and machining path for NC tool. Therefore, multiple variables are required in NC code.

It was concluded that creating identical cutting area for every correction passage would be the most suitable and reasonably simple method. Thus, only cutting depth of the area would vary according to amount and angular position of unbalance to be removed. 3D-model and material removal calculations were done for the milling area, where angular position of unbalance would determine which two correction passages would be milled, and amount of unbalance would determine cutting depth of each correction passage (see appendix 3 for calculations). An experimental test was carried out to remove average amount of unbalance from the most typical impeller model in balancing during 2018. Figure 26 shows 3D-model and setup for correction by CNC milling.

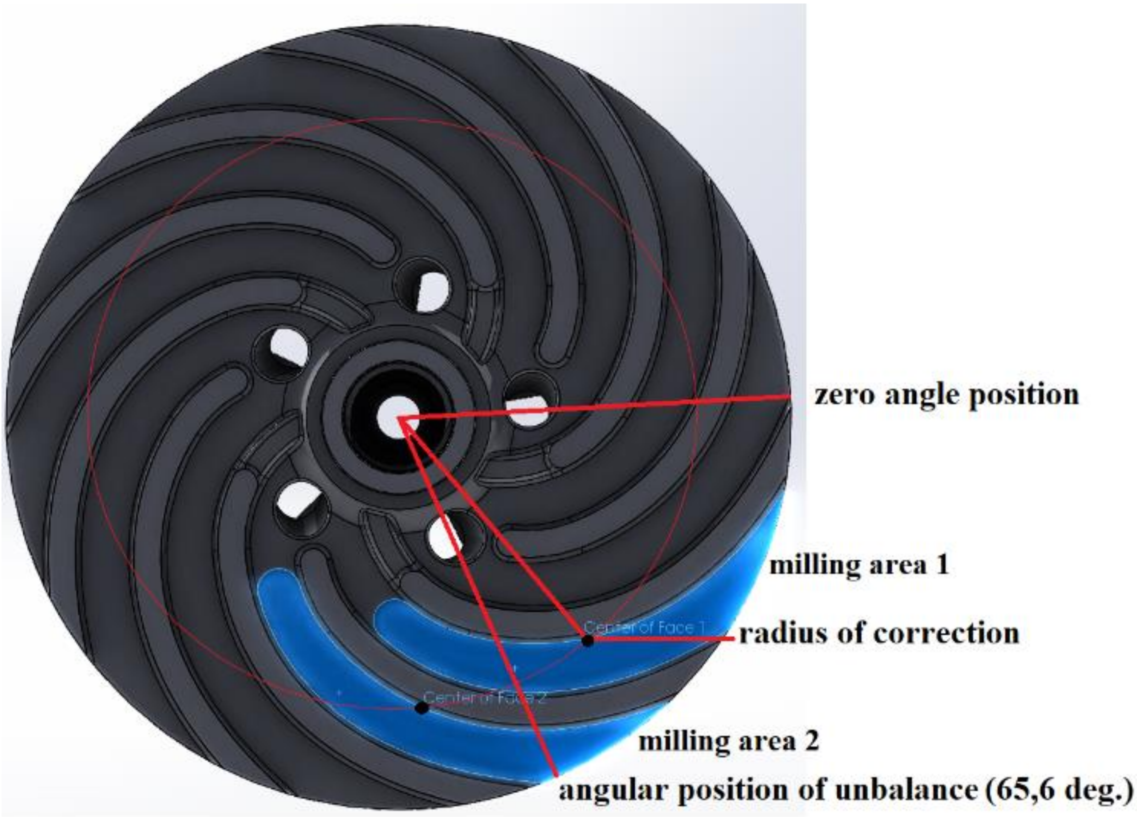


Figure 26. Setup for unbalance correction by CNC milling. Correction areas indicated in blue are identical for each correction passage, cutting depth varies according to amount of unbalance and its angular positions.

As can be seen from figure 26, theoretical radius of correction indicated with red circle circulates through center of face of each correction passage. Actual milling is done from the blue areas indicated in figure 26, while cutting depth of areas is determined by angular position and amount of unbalance as in appendix 3. Figure 27 shows test impeller after correction by CNC-milling.

Figure 27. Impeller after correction by CNC-milling. Achieved surface quality meets the requirements.

As figure 27 shows, surface quality after milling remains smooth. Additionally, edges of milling areas meet the requirements and impeller could be approved in terms of surface quality. Table 36 shows numerical results of performed correction by CNC-milling.

Table 36. Numerical results of correction by CNC-milling. $U_{initial}$ *= initial unbalance,* U_{per} *= permissible residual unbalance,* U_{res} *= residual unbalance.*

Impeller size	5
weight (kg)	designed: 58,2 / actual: 56,4
diameter (mm)	designed: 455 / actual: 456
$U_{initial}$ **(g)**	120
radius of correction (mm)	designed: 227,5 / actual: 228
balance quality grade	G 6.3
U_{per} **(g)**	10,05 at r = 228 mm
U_{res} **after CNC milling (g)**	6,9 at r = 228 mm

As table 36 indicates, U_{res} achieved by CNC milling is below U_{per}, which means that balanced impeller meets balance quality grade G 6.3 requirements and unbalance measurement result would be approved. In theory, calculations should have resulted in zero unbalance, but as table 36 shows there exists variation in designed and actual properties of impeller. After milling it was noticed that cutting depth was not identical in the whole correction area. This indicates that the cast surface of hub disk was not straight due to manufacturing error which lead to U_{res} of 6,9 g instead of being zero. In conclusion, automatic unbalance correction is possible by examined method, but manufacturing errors of castings create uncertainty. Therefore, a further study of effects of manufacturing errors to balancing should be conducted during the detailed design phase.

9.3 Conclusions about challenges faced during study

Evaluation, selection, justification and implementation planning of the most valuable AMT concept for automatization of impeller balancing proved to be a complex problem, as stated in numerous studies. (Nath & Sarkar 2017; Garcia & Alvarado 2012; Goyal & Grover 2012). From problems recognized in AMT implementation by Garcia and Alvarado (2012, p. 130), installation and setup, maintenance, investment justification process and decision and analysis process proved to be relevant problems also in automatization of impeller balancing. Creating a proper requirements list and identifying the most relevant evaluation criteria was challenging and updates were done several times. For example, amount of preparations needed generally was changed to amount of preparations needed when changing impeller type, as general preparations overlap with fixture and clamping capability that was also one criterion. This way overlapping was limited, and evaluation system improved.

As target company is early adopter, risks are bigger than for late adopters of new technology. The importance of cooperating with industry experts is emphasized as the investment requires expertise on at least three specific industries; balancing, machining and automation. Detailed design phase requires exchanging the best practices and knowledge to each other, so that typical mistakes related to each specialized field could be avoided. The most significant aspects in automatization of impeller balancing are identified as follows:

- Variation of impeller types: heavy variation in impeller size and design causes challenges in planning automation. Parameters must be adjusted differently for each manufacturing cycle.
- Casting as a manufacturing method: casting creates relatively large manufacturing errors, which means that dimensions and shapes of one impeller model may vary significantly between manufactured pieces. AMT concept should be able to identify and react to dimensions and shapes that deflect from the manufacturing drawing.

- Complex impeller design combined with high quality requirements: complex impeller design and limitations of permissible material removal area lead to challenging demands in area identification, toolpath generation and properties of CNC machine. Additionally, workpiece handling and fixing requires specific solutions due to complex design.
- Specified and detailed manufacturing process escalating costs of automation: as impeller balancing includes details and following strictly given standards and guidelines, costs of creating automatized system are increased and therefore utilization rate requirements for automatized manufacturing cell are also increased.
- Capability of reacting to design changes of impellers: lifecycles of different impeller designs should be considered regarding the investment. If new models of impellers are introduced in the future and they become eventually popular, capability of manufacturing concept to adapt new impeller designs should be examined.

9.4 Reliability and objectivity aspects

Examined three manufacturing concepts were based on cooperation with concept suppliers and OEM's. Concepts were formed according to suppliers' capabilities to match requirements of investments. Selection of concepts and suppliers included in this study was based on background study of commercial www-sources. The most potential concept suppliers were contacted and as a result, three most promising manufacturing concepts were selected to be included in this study. Therefore, there are no guarantees that selected three concepts with related suppliers and OEM's are the best available in the market. Still, examined concepts differed significantly from each other which means that comparison drew a line between various operational options.

Considering expert opinions and preliminary quotations from suppliers increased validity of the study. This approach proved to be appropriate as other study also found that issues are likely to occur in AMT projects and early adopters should cooperate actively with industry experts instead of starting design from the beginning. This way common design mistakes related to each industry, balancing, machining and automation, could be avoided.

Source triangulation of scientific literature, target company's internal sources and commercial sources increased reliability of the research. Numerous cross references, such as between balancing standards and scientific literature, increased also reliability of the collected. This way information from each source was observed critically and compared to other sources. Objectivity of value analysis was increased by utilizing pairwise comparison method to determine weights for main evaluation criteria. Geometric averages were used instead of arithmetic averages when calculating grades of main criteria, so that low grades would affect more to overall grade. This way value of manufacturing concept with few extremely poor properties would be reduced.

Sub-criteria grading between different manufacturing concepts was based on quantitative and qualitative values. Values were mostly based on preliminary quotations of suppliers and specifications of utilized machinery. It should be noted that these values might change during detailed design phase.

Adjusting value obtained from value analysis with relative risk level obtained from risk analysis provided more reliable results of concept values. Reliability of the study was also significantly improved by generating an example of automatic unbalance correction method by milling and testing it in practice. Thus, it verified that automatic correction by milling works in practice, but also pointed out aspects that must be considered to make automatic correction work without risk of errors.

Selection and implementation of AMTs is a widely researched area. Numerous studies stated that AMT selection and implementation process is a complex problem (Nath & Sarkar 2017; Garcia & Alvarado 2012; Goyal & Grover 2012). Furthermore, evaluating the effectiveness of AMT proved to be a complex task as concluded in a review of 77 studies conducted by Goyal and Grover (2012, p. 262). This emphasized the need for risk analysis to be included in comparison of manufacturing concepts for impeller balancing. Figure 28 illustrates deviation and number of published scientific articles related to implementation, evaluation and selection of AMT.

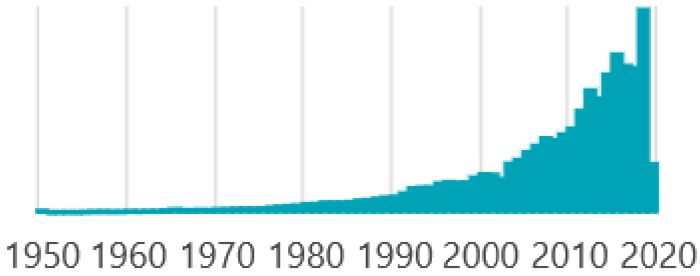


Figure 28. Search results of scientific articles with key words "AMT implementation" OR “AMT evaluation” OR “AMT selection” at LUT Finna’s international e-materials advanced search. Total number of scientific articles found between years 1950–2018 was 386370.

As figure 28 states, number of publications has been rapidly growing from the beginning of 21st century. It can also be seen that the fastest growth in number of publications takes place after 2010. This indicates that there exists a significant need to study these topics.

Typical problems that have emerged in several similar studies regarding evaluation, selection and implementation of AMT were also identified during this study. Finding comprehensive evaluation platform proved to be challenging. Evaluation criteria of value analysis were derived from requirements list that was updated several times and ultimately approved by development manager. Nevertheless, determining what evaluation criteria should fit the purpose best was difficult and further research may have been required to improve the validity of selected evaluation criteria and content of requirements list.

Risk priority classes (RPC) in risk analysis are subjective opinions and changing classification and given weights for each RPC would change results of the study. It may also be that some critical risks were not identified in the analysis. Ultimately, utilized risk analysis method proved to be a proper way to compare relative risk levels of different manufacturing concepts, although obtained risk levels are not comparable to any risk levels outside of this study and cannot be used to identify significance of risks in general.

Goal of this study was to identify and select the most valuable manufacturing concept for impeller balancing at target company and develop a proper evaluation system to justify investment. The recommendation of the most suitable manufacturing concept was based on adjusting value with relative risk level. Therefore, key properties, investment costs and the most significant risks were considered in evaluation and selection process to form a comprehensive justification method for selected manufacturing concept.

Study results are sensitive to suppliers included in this study. It is possible that some information received from suppliers was interpret incorrectly, which would affect the grading of value analysis and risk analysis. Therefore, study results should be observed with a certain level of criticality and results should be discussed also with industry experts and suppliers that were not included in study.

9.5 Further research topics

Based on the conducted study, essential topics for further research were recognized with the assumption that target company will decide to proceed with manufacturing concept 3. Research topics are listed in order of priority as follows:

1. Effects of casting's manufacturing errors to automatic unbalance correction and methods to compensate them
2. Optimization of material flow in automatic balancing cell
3. Automatization of bur removal
4. Methods to identify allowable material removal area of impellers
5. Optimization of toolpath generation algorithms
6. Comparison of commercial balancing machines and machining centers
7. Financial effects caused by intangible benefits of automatizing balancing
8. Possibilities of automatizing complete impeller manufacturing chain
9. Methods to eliminate adverse effects of unbalanced rotor in centrifugal pump

List presented above can also be used as a checklist during the detailed design phase. Recommendation to examine at least the top three topics comprehensively is given according to the study conducted.

10 SUMMARY

This study consisted of examining and comparing potential manufacturing concepts for automatization of impeller balancing at target company. Ultimately, investment for the most valuable manufacturing concept was recommended and justified. Research problem consisted of challenging working conditions and heavy manual work combined with strict quality demands in balancing, which caused impeller quality and lead time to be dependent of employee's performance. Goal of the study was to identify the most valuable manufacturing concept for automatization of impeller balancing at target company and develop a proper evaluation system to justify the investment.

Manufacturing concept 3 proved to be the most valuable concept for impeller balancing. Main arguments consisted of production flexibility, options to extend functionality, operational reliability and high level of automation eliminating disadvantages of existing balancing concept. Manufacturing concepts 1 and 2 benefitted for having simple and compact cell layouts with smaller investment costs, but low level of automation and risks related to operational reliability reduced values of both concepts below concept 3.

The detailed design phase proved to be essential to ensure smooth operation, conduct proper risk management and ensure successful implementation of concept 3. Integrating all functions together will require significant resources from target company and concept 3 supplier. It would take approximately one year from the beginning of detailed design phase to actual start-up of the manufacturing cell at target company's factory, due to complexity of manufacturing concept 3.

Justification of investment proved to be challenging for manufacturing concept 3. Direct financial measures alone were not applicable for proper justification, as investment would provide considerable intangible benefits that require further research to evaluate their financial effects. By investing to manufacturing concept 3, significant improvements can be achieved in impeller balancing in terms of lead time and impeller quality, working conditions and competitive advantage gained in comparison to direct competitors.

LIST OF REFERENCES

Adamkowski, A., Henke, A. & Lewandowski, M. 2016. Resonance of torsional vibrations of centrifugal pump shafts due to cavitation erosion of pump impellers. In: Engineering Failure Analysis: 70. Pages 56–72.

Albraik, A., Althobiani, F., Gu, F. & Ball, A. 2012. Diagnosis of Centrifugal Pump Faults Using Vibration Methods. In: Journal of Physics: Conference Series 364. 12 pages.

Basic theory of dynamic balancing. ABRO lecture notes. [ABRO Balancing www-sites]. [Referred 6.3.2019]. 5 pages. Available as PDF: http://abrobalancing.com/pdf/LECTURE_NOTES_(ABRO).pdf

Centrifugal Pump Handbook. Sulzer Pumps Ltd. 2010. 3rd edition. 289 pages.

Dynamic balancing machines. ABRO lecture notes. [ABRO Balancing www-sites]. [Referred 6.3.2019]. 9 pages. Available as PDF: http://abrobalancing.com/pdf/LECTURE_NOTES_(ABRO).pdf

End suction single stage centrifugal pumps. 2018. [Sulzer www-pages]. [Referred 13.12.2018]. 24 pages. Available as PDF-file: https://www.sulzer.com/-/media/files/products/pumps/single-stage-pumps/brochures/ahlstarendsuctionsinglestage_e10083.ashx?la=en

Energy-Efficient Machine Tool Technologies, For Any Size Shop. 2016. [Okuma www-sites]. [Referred 19.4.2019]. 8 pages. Available as PDF at: https://www.okuma.com/stuff/contentmgr/files/0/143c354d61f2562efb3e2a8bd72166a0/files/okuma_energyefficientmachinetooltechnologies_whitepaper_final_high_res.pdf

García, J. & Alvarado, A. 2012. Problems in the implementation process of advanced manufacturing technologies. In: The International Journal of Advanced Manufacturing Technology: 64:1-4. Pages 123–131.

Goyal, S. & Grover S. 2012. Advanced manufacturing technology effectiveness: A review of literature and some issues. In: Frontiers of Mechanical Engineering: 7:3. Pages 256–267.

Heindel, S., Becker, F. & Rinderknecht, S. 2017. Unbalance and resonance elimination with active bearings on a Jeffcot Rotor. In: Mechanical Systems and Signal Processing: 85. Pages 339–353.

Semi-structured interviews 2019. Employees interviewed: Hakala, J., Hänninen, K., Lindqvist, J., Rautjärvi, J., Rinne, M., Puonti, R., Hurtta, S., Pulsa, T., Pakkala, T & Özgünes, I. Kotka: 1.1.2019–25.2.2019. Interviewed by Mikko Ryhänen. Notes in possession of the interviewer.

Kalmegh, A. & Bhaskar, S. 2012. Dynamic Balancing of Centrifugal Pump Impeller. In: International Journal of Emerging Technology and Advanced Engineering: 2:6. Pages 409–413.

Kumar, B., Diwakar, G., & Satynarayana M. 2012. Determination of Unbalance in Rotating Machine Using Vibration Signature Analysis. In: International Journal of Modern Engineering Research (IJMER): 2:5. Pages 3415–3421.

Matsushita, O., Tanaka, M., Kanki, H., Kobayashi, M. & Keogh, P. 2017. Volume 1. Basic Rotordynamics: Introduction to Practical Vibration Analysis. In: Vibrations of Rotating Machinery. In: Mathematics for Industry: 16. 360 pages.

Meskanen, S. 2017. Valukomponentin suunnittelun perusteita. In: Suunnittelijan perusopas. [ValuAtlas www-pages]. [Referred 27.12.2018]. [Updated 2017]. 23 pages. Available as PDF-file: http://www.valuatlas.fi/tietomat/docs/perusopas_13.pdf

Nath, S. & Sarkar, B. 2017. Performance evaluation of advanced manufacturing technologies: A De novo approach. In: Computers & Industrial Engineering: 110. Pages 264–378.

Paro, J., Hänninen, H. & Kauppinen, V. 2001. Tool wear and machinability of HIPed P/M and conventional cast duplex stainless steels. In: Wear: 249. Pages 279–284.

Pirttilahti, P. 2019. NC-point Oy. Kotka: free-form interview 9.1.2019. Interviewed by Mikko Ryhänen. Notes in possession of the interviewer.

Päkki, V. 2019. Tapio Päkki Oy. [private e-mail]. [Received 12.04.2019]. [Referred 13.04.2019].

Quotation attachment of supplier 1. 2019. [Received 18.3.2019]. [classified document].

Quotation and specifications of supplier 1. 2019. [Received 18.3.2019]. [classified document].

Quotation and specifications of supplier 2. 2019. [Received 8.4.2019]. [classified document].

Quotation and specifications of supplier 3. 2019. [Received 28.3.2019]. [classified document].

Ratia, T. 2019. Development Manager, Sulzer Pumps Finland Oy. Kotka: free-form interview 03.01.2019. Interviewed by Mikko Ryhänen. Notes in possession of the interviewer.

Ruehs, A. 2013. When to low speed balance. [Toshiba www-pages]. [Referred 20.03.2019]. Available as PDF-file: https://www.toshiba.com/taes/cms_files/when_low_speed_balance.pdf

Safaieh, M., Nassehi, A. & Newman S. 2012. A novel methodology for cross-technology interoperability in CNC machining. In: Robotics and Computer-Integrated Manufacturing: 29. Pages 79–87.

Suhner Powermaster. [Suhner www-sites]. [Rederred 18.4.2019]. 4 pages. Available as PDF-file: http://www.suhner-automation-expert.com/domains/suhner-automation-expert_com/data/free_docs/POWERmaster_BEX15.pdf

SFS-ISO 21940-2. 2017. Mechanical vibration – Rotor balancing – Part 2: Vocabulary. 1st edition. Suomen Standardisoimisliitto SFS ry. 28 pages.

SFS-ISO 21940-11. 2017. Mechanical vibration – Rotor balancing – Part 11: Procedures and tolerances for rotors with rigid behaviour. 1st edition. Suomen Standardisoimisliitto SFS ry. 29 pages.

SNS End Suction Single Stage Centrifugal Pumps. 2017. [Sulzer www-pages]. [Referred 12.12.2018]. 11 pages. Available as PDF-file: https://www.sulzer.com/-/media/files/products/pumps/single-stage-pumps/brochures/sns_single_stage_centrifugal_pumps_e10333.ashx

Taneja S. 2013. Effect of Unbalance on Performance of Centrifugal Pump. In: International Journal of Scientific & Technology Research: 2:8. Pages 56–60.

Tiwari R. 2010. Dynamic Balancing of Rotors. Chapter 13. In: Theory & Practice of Rotor Dynamics. NPTEL. Pages 766–787.

VIRIO. [Schenck www-pages]. [Referred 27.2.2019]. Available at: https://schenck-rotec.com/products/product-finder/product-detail-page/en-virio.html

VIRIO RM1041-1e. [Product brochure]. [Schenck www-pages]. [Referred 27.2.2019]. 12 pages. Available as PDF at: https://schenck-rotec.com/products/product-finder/product-detail-page/en-virio.html

Williams, R. 2013. Handy checklist for preventive maintenance. [Okuma www-sites]. [Referred 19.4.2019]. Available at: https://www.okuma.com/handy-checklist-for-preventive-maintenance

Appendix 1: Questions presented in semi-structured interviews of balancing employees

- What are your responsibilities at work?
- How suitable are existing balancing machines and equipment for performing balancing?
- How do you feel about balancing, how does it show in your working?
- How relevant is balancing in terms of pump's lead time?
- What kind of effect balancing has in pump's quality and what kind of guidelines and quality requirements exist in balancing?
- How many measuring-correction cycles are typically needed in balancing and what factors affect the number?
- Could existing balancing process be improved somehow? If yes, how?
- How would you change existing balancing process?
- Do you feel that increasing automation in balancing could provide benefits and where could automation be utilized in balancing?

Appendix 2: Grading system of value analysis.

Note: numbers after symbols and abbreviations indicate the concept number.

Phase 1

EVALUATION CRITERIA	CONCEPT 1	CONCEPT 2	CONCEPT 3
Impeller size scope	x	x	x
Material removal capacity	x	x	x
Fixture & clamping capability	x	x	x
Key automation ratio	x	x	x
FLEXIBILITY	**GA1,F**	**GA2,F**	**GA3,F**
Lead time	x	x	x
Measure uncertainty	x	x	x
Machining accuracy	x	x	x
Need of preparations*	x	x	x
PERFORMANCE, GA	**GA1,P**	**GA2,P**	**GA3,P**
Machine tool wear	x	x	x
Wear of rotating components	x	x	x
Calibration need	x	x	x
Scope of maintenance	x	x	x
DURABILITY, GA	**GA1,D**	**GA2,D**	**GA3,D**

x = grade given for specific sub-criterion on a scale of 1–5
GA = geometric average of sub-criteria of specific main criteria

Phase 2

	CONCEPT 1	CONCEPT 2	CONCEPT 3
Flexibility (Wf · GA)	Wf · GA1,F	Wf · GA2,F	Wf · GA3,F
Performance (Wp · GA)	Wp · GA1,P	Wp · GA2,P	Wp · GA3,P
Durability (Wd · GA)	Wd · GA1,D	Wd · GA2,D	Wd · GA3,D
Property points = ∑ (W · GA)	**∑,1**	**∑,2**	**∑,3**

W = weight factor based on pairwise comparison of main criteria

Phase 3

	CONCEPT 1	CONCEPT 2	CONCEPT 3
Relative cost (RC)	RC1 / RC1	RC2 / RC1	RC3 / RC1

Relative costs calculated by using concept 1 cost as reference.

Phase 4

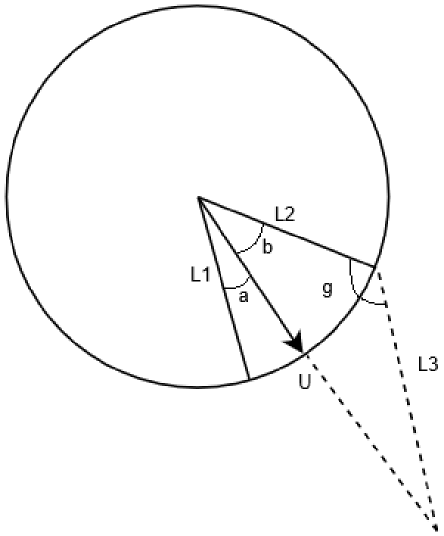
	CONCEPT 1	CONCEPT 2	CONCEPT 3
Value = [∑ (W · GA)] / RC	V1	V2	V3

V = value of specific concept
Value = property points / relative cost

Appendix 3: Calculations for automatic unbalance correction by CNC milling

U = unbalance vector
a = alfa
b = beta
g = gamma

L1 = line through milling area 1 center of face
L2 = line through milling area 2 center of face
L3 = parallel to L1



			Formula
Data for calculations			
initial unbalance mass, Um		120 g	*Measured in balancing machine*
radius of unbalance, Ur		227,5 mm	*impeller diameter / 2*
unbalance, U		27300 gmm	*Um*Ur*
angular position of unbalance, a1		65,57 deg	*Measured in SolidWorks*
horizontal dist. from impellers cent. of mass to cent. of face of milling area, d1		189,05 mm	*Measured in SolidWorks*
alfa		23,36 deg = 0,408 rad	*Measured in SolidWorks*
beta		12,64 deg = 0,221 rad	*Measured in SolidWorks*
gamma		144 deg = 2,513 rad	*Measured in SolidWorks*
sin(a)		0,397	*sin(alfa)*
sin(b)		0,219	*sin(beta)*
sin(g)		0,588	*sin(gamma)*
Milling area 1			
unbalance in milling area 1, U1		10163 gmm	*U/sin(g)*sin(b)*
material to be removed, M1		53,76 g	*U1/d1*
area 1, A1		4779,25 mm2	*Measured in SolidWorks*
density of material, d		0,0077 g/mm3	*Based on material properties*
Milling parameters for area 1			
cutting depth 1		1,46 mm	*M1/(A1*d)*
starting point of milling 1	angle =	12,09 deg	*Measured in SolidWorks*
	radius =	227,5 mm	*impeller diameter / 2*
Milling area 2			
unbalance in milling area 2, U2		18416 gmm	*U/sin(g)*sin(a)*
material to be removed, M2		97,41 g	*U2/d1*
area 2, A2		4779,25 mm2	*Measured in SolidWorks*
density of material, d		0,0077 g/mm3	*Based on material properties*
Milling parameters for area 2			
cutting depth 2		2,65 mm	*M2/(A2*d)*
starting point of milling 2	angle =	48,09 deg	*Measured in SolidWorks*
	radius =	227,5 mm	*impeller diameter / 2*

Appendix 4: preventative maintenance checklist for CNC machines

OKUMA
OPEN POSSIBILITIES

PREVENTIVE MAINTENANCE CHECKLIST

EVERY DAY

1. Check the hydraulic pressure to make sure it's at 4.5 MPa
2. Check the hydraulic fluids to make sure they're at the right operating level
3. Check to make sure the chuck pressure is at the right operating pressure and grease chuck according to manufacturer's recommendation
4. Make sure the way lube level is at the right operating level, and replenish if needed
5. If your CNC machine has a cooling system, make sure the cooling unit level is at the right operating level
6. Clean the chips out of the chip pan
7. Clean off the window of the door and the light so you can see inside your machine
8. Wipe down any stainless steel way covers and lubricate them with hydraulic oil so they move smoothly
9. On a weekly basis (or every 40 hours) take the filter off the CNC control cabinet and clean it so air will be able to flow through for cooling

EVERY THREE MONTHS (or 500 hours)

1. Check and grease the chain on the chip conveyor
2. Check and clean the filters on the coolant tank

NEXT QUARTERLY MAINTENANCE DUE:

EVERY SIX MONTHS (or 1,000 hours)

Contact your local distributor to have the following PM performed by a certified Okuma Engineer:

1. Have the coolant tank cleaned of sludge, chips, and oil
2. Have the chuck and jaws taken off the machine and cleaned
3. Have the hydraulic tank drained and replace the hydraulic oil with fresh hydraulic oil—also have the line filter and suction filter changed
4. Have the radiator cleaned and make sure the radiator fins are straight
5. Have the lubrication unit drained and cleaned out—then add fresh way lube
6. If your machine is equipped with a cooling unit, have the unit drained and refilled
7. Have the leveling of your machine checked and adjust if necessary
8. Have all way wipers inspected for any damage—clean and replace any wipers that are damaged

NEXT BIANNUAL MAINTENANCE DUE:

ONCE A YEAR (or 2,000 hours)

Contact your local distributor and have the following inspected:

1. Have the headstock checked for taper
2. Have the spindle checked for radial and end play
3. Have the chuck cylinder checked for run out
4. Have the tailstock checked for taper
5. Have the turret parallelism and inclination checked
6. Have your distributor run a backlash program to check the backlash in X- and Z-axis and adjust if necessary
7. Have your distributor check the X- and Z-axis gibs and adjust if necessary

NEXT ANNUAL MAINTENANCE DUE:

Available for download at: https://site.okuma.com/preventive-maintenance-checklist-download?hsCtaTracking=a513e692-2aa5-4f06-a95f-3b7c4bff8afe%7C7c0d8558-6207-424c-ae63-2c7a2e9f4c51