AHP-based support tools for initial screening of manufacturing reshoring decisions

Movin Sequeira
Department of Industrial Product, Production Development and Design, Jönköping University, Jönköping, Sweden

Per Hilletofth
Department of Industrial Engineering and Management, University of Gävle, Gävle, Sweden and Department of Industrial Product, Production Development and Design, Jönköping University, Jönköping, Sweden, and

Anders Adlemo
Department of Computer Science and Informatics, Jönköping University, Jönköping, Sweden

Abstract

Purpose – The existing literature expresses a strong need to develop tools that support the manufacturing reshoring decision-making process. This paper aims to examine the suitability of analytical hierarchy process (AHP)-based tools for initial screening of manufacturing reshoring decisions.

Design/methodology/approach – Two AHP-based tools for the initial screening of manufacturing reshoring decisions are developed. The first tool is based on traditional AHP, while the second is based on fuzzy-AHP. Six high-level and holistic reshoring criteria based on competitive priorities were identified through a literature review. Next, a panel of experts from a Swedish manufacturing company was involved in the overall comparison of the criteria. Based on this comparison, priority weights of the criteria were obtained through a pairwise analysis. Subsequently, the priority weights were used in a weighted-sum manner to evaluate 20 reshoring scenarios. Afterwards, the outputs from the traditional AHP and fuzzy-AHP tools were compared to the opinions of the experts. Finally, a sensitivity analysis was performed to evaluate the stability of the developed decision support tools.

Findings – The research demonstrates that AHP-based support tools are suitable for the initial screening of manufacturing reshoring decisions. With regard to the presented set of criteria and reshoring scenarios, both traditional AHP and fuzzy-AHP are shown to be consistent with the experts’ decisions. Moreover, fuzzy-AHP is shown to be marginally more reliable than traditional AHP. According to the sensitivity analysis, the order of importance of the six criteria is stable for high values of weights of cost and quality criteria.

Research limitations/implications – The limitation of the developed AHP-based tools is that they currently only include a limited number of high-level decision criteria. Therefore, future research should focus on adding low-level criteria to the tools using a multi-level architecture. The current research contributes to

© Movin Sequeira, Per Hilletofth and Anders Adlemo. Published by Emerald Publishing Limited. This article is published under the Creative Commons Attribution (CC BY 4.0) license. Anyone may reproduce, distribute, translate and create derivative works of this article (for both commercial and non-commercial purposes), subject to full attribution to the original publication and authors. The full terms of this license may be seen at http://creativecommons.org/licences/by/4.0/legalcode.

The authors thank the anonymous reviewers for their careful reading of the manuscript and their many insightful suggestions. This work has been financed by The Knowledge Foundation (KK-stiftelsen, grant number: 20200058).
the body of literature on the manufacturing reshoring decision-making process by addressing decision- 
making issues in general and by demonstrating the suitability of two decision support tools applied to the 
manufacturing reshoring field in particular.

**Practical implications** – This research provides practitioners with two decision support tools for the 
initial screening of manufacturing reshoring decisions, which will help managers optimize their time and 
resources on the most promising reshoring alternatives. Given the complex nature of reshoring decisions, the 
results from the fuzzy-AHP are shown to be slightly closer to those of the experts than traditional AHP for 
initial screening of manufacturing relocation decisions.

**Originality/value** – This paper describes two decision support tools that can be applied for the initial 
screening of manufacturing reshoring decisions while considering six high-level and holistic criteria. Both 
support tools are applied to evaluate 20 identical manufacturing reshoring scenarios, allowing a comparison 
of their output. The sensitivity analysis demonstrates the relative importance of the reshoring criteria.

**Keywords** Quantitative, Decision-making, AHP, Fuzzy-AHP, Manufacturing relocation, Reshoring, Initial screening

**Paper type** Research paper

1. **Introduction**

Over the past few years, the manufacturing reshoring phenomenon has elicited an increased 
interest among scholars, practitioners, and policymakers (Moser, 2013; Tate et al., 2014; Zhai et al., 2016). This phenomenon is described as the repatriation of previously owned 
manufacturing or supplier activities, back to the manufacturer’s home country (Gray et al., 2013). In this context, reshoring refers to a location decision that is independent of whether 
the manufacturing is insourced or outsourced (Barbieri et al., 2018). Although reshoring has 
been practiced for more than a decade, the prominent surge in academic research has 
occurred after 2016 (Barbieri et al., 2018). Given that this area of research is still evolving, 
both industry and academia are finding it difficult to fully comprehend the reshoring 
phenomenon (Boffelli et al., 2020). Different aspects of reshoring have been studied, such as 
its definition, the types of industries involved, (de)motivations for reshoring, countries 
involved, and the duration (Ancarani et al., 2015; Barbieri et al., 2018; Fratocchi et al., 2016; 
Wiesmann et al., 2017). Even so, the decision-making reshoring process remains poorly 
understood since it is a viscerally complex process (Barbieri et al., 2018). Due to this 
complexity, managers tend to rely on their past experiences or heuristic approaches in 
decision-making when dealing with reshoring issues (Boffelli et al., 2020; Gray et al., 2017). 
To provide practical and useful decision support, there is a need to develop tools that 
facilitate accurate and resilient reshoring decisions (Hilletofth et al., 2019a).

This need to develop decision support tools for managers to make accurate and resilient 
manufacturing reshoring decisions has been highlighted as a highly prioritized research 
area (Barbieri et al., 2018; Stentoft et al., 2016b; Wiesmann et al., 2017). Additionally, and 
especially considering the recent Covid-19 pandemic, the global economy is potentially 
facing a grave situation as closure of manufacturing facilities and travel restrictions have 
severely disrupted global supply chains (OECD, 2020). This global event has inexorably 
raised concerns regarding the uncertainty and vulnerability of the supply chains. Early 
secondary data from press releases have alluded to the triggering role played by the 
pandemic in reshoring to Europe (Barbieri et al., 2020). Against this backdrop, future supply 
chains are required to augment their ability to prepare for similar eventualities by providing 
esential functions to recover from a post-pandemic vulnerability (Barbieri et al., 2020; Golan et al., 2020). A proactive approach is necessary, for example, analyzing the timing of 
manufacturing reshoring within the supply chain. Thus, decision support tools for 
manufacturing reshoring are required, since events with global ramifications, such as Covid-
19, can strongly influence decision-making processes. Additionally, with the rapid technological advancements in artificial intelligence (AI) and big data analytics, the desired decision support needs to be in a digital form (Baryannis et al., 2019). Hence, these highly relevant decision-making issues concerning manufacturing reshoring must be urgently addressed.

Extensive reshoring decision-making models have been built using system dynamics that entails a cost perspective (Gray et al., 2017). When studying manufacturing reshoring decision-making, the modeling approach is deemed appropriate because it is possible to decipher the relationship between the variables and the final decision (Bertrand and Fransoo, 2002; Hilletoft and Lättiä, 2012). Decision-making models based on multi-criteria decision-making (MCDM) methods are increasingly applied within the wider operations management domain (Vaidya and Kumar, 2006). The MCDM methods provide a way to identify and choose the “best” alternative based on the comparison of the decision criteria (Rao, 2013). Many such MCDM methods have been explored to solve similar problems within the operations management, such as supplier selection (Banasik et al., 2018). Consequently, it is reasonable to assume that these methods could also be applied to manufacturing reshoring decisions. Some studies have leveraged already existing MCDM methods to explore manufacturing reshoring decisions (Pal et al., 2018a; Sarder et al., 2014; White and Borchers, 2016). However, these studies have a limited perspective regarding the decision criteria. This limitation has been overcome in this study by considering a holistic set of decision criteria.

MCDM methods are interesting from a manufacturing reshoring decision-making point of view and it has been suggested that even more research using MCDM methods should be conducted in the manufacturing reshoring domain (Sarder et al., 2014). One specific MCDM method which has been explored within the manufacturing reshoring decision-making domain is the analytical hierarchy process (AHP). The so-called traditional AHP is based on crisp comparisons between different criteria and is thus, not designed to handle uncertainty. Manufacturing reshoring decisions, however, involve uncertainty due to the dynamics in the global environment that needs to be taken into consideration (Kinkel, 2012). To incorporate uncertainty in the reshoring decision, fuzzy logic is integrated into the traditional AHP, otherwise known as fuzzy-AHP (van Laarhoven and Pedrycz, 1983; Sagar et al., 2015). Fuzzy-AHP has been explored in the manufacturing reshoring decision-making domain where three criteria from the operations strategy have been used (Pal et al., 2018a; White and Borchers, 2016). However, there is still a need to incorporate a wider range of operations strategy criteria. The manufacturing reshoring domain is underdeveloped with regard to MCDM methods when compared to closely related domains, such as supplier selection and evaluation domain, where a plethora of research related to MCDM methods exists (Emrouznejad and Marra, 2017). Having said that, there does exist a need to develop similar decision-making methods for the manufacturing reshoring decision-making domain. This paper attempts to fill this research gap within the purview of manufacturing reshoring decision-making.

The purpose of this study is to investigate the suitability of AHP-based tools for the initial screening of manufacturing reshoring decisions. The goal of initial screening is to identify the feasibility of continuing with the following steps of the reshoring decision process as early as possible (Figure 1). Arriving at an early decision of not continuing the reshoring process can save a lot of resources. The first stage in this study entails the development of two AHP-based tools. The first tool is premised upon crisp comparisons of the reshoring criteria, while the second is based on fuzzy comparisons. The criteria used by the two tools were obtained from the reshoring literature. Then, a panel of industry experts
was involved in an overall comparison of the criteria, following which the weights of the criteria obtained from the tools were used in the evaluation of twenty reshoring scenarios for initial screening purposes. The output of the tools suggests whether the scenarios are interesting to further evaluate reshoring and spend both time and resources in the decision-making process. The reliability of the tools was measured as a difference between their output and the opinion of industry experts on reshoring scenarios. Finally, a sensitivity analysis was performed to evaluate the stability of the results generated by the decision support tools. The scientific output of the research presented is threefold. First, it addresses a relevant research gap related to manufacturing reshoring decision-making by presenting two decision support tools. Second, holistic qualitative and quantitative criteria used in the developed decision support tools make the decision support generic to different types of companies that are evaluating the reshoring option. Third, a comparison between the crisp and fuzzy-AHP points out which of the two performs the best for the initial screening of manufacturing reshoring decisions.

The rest of the paper is outlined as follows. Section 2 provides a review of related research within manufacturing reshoring decision-making and AHP-based tools. Section 3 elucidates the details of the two AHP-based support tools for manufacturing reshoring decision-making. Section 4 presents the results of the research concerning the final criteria weights, the evaluation of the reshoring scenarios, and the results drawn from the sensitivity analysis. Section 5 discusses the obtained results in relation to the literature. Section 6 presents the implications of this study for both practice and society, whereas Section 7 concludes the paper and presents some future lines of research.

2. Literature review
This section provides an overview of literature on the manufacturing reshoring decision-making process and AHP for decision-making.

2.1 Manufacturing reshoring decision-making process
The manufacturing reshoring decision-making process comprises five generic steps (Bals et al., 2016), which are as follows:

- controlling the boundary of the company;
- analyzing the current performance of the company;
- obtaining information on possible reshoring alternatives;
- analyzing the data for reshoring alternatives; and
- making the reshoring decision.

![Figure 1. Initial screening tools in the manufacturing reshoring decision-making process](image-url)
There is a limited understanding of various stages and activities within each of these steps. It has been shown that the manufacturing reshoring decision-making process starts with a ‘trigger’, caused by either an event, opportunity, or problem (Barbieri et al., 2020; Benstead et al., 2017; Boffelli et al., 2018). This trigger then leads to the identification of a gap between the expected and the current performance of the company (step 1) (Gray et al., 2017). A data collection and analysis are realized to evaluate the existing performance of the company. During this process (step 2), the company needs to obtain information about the costs and the investment required, existing and required production capacity, machinery selection, or the current state of a new product development process (Boffelli et al., 2020). Next, (step 3) the company assembles information on the possible reshoring alternatives. For example, some of the alternatives could be to outsource to a local supplier, to relocate to a different region within the home country, or to relocate to the headquarters within the home country. Thereafter, (step 4) the company analyzes the data for the different reshoring alternatives, before arriving at the reshoring decision (step 5). When making this decision, it should be noted that reshoring is only one among several other alternatives that companies pursue after offshoring (Bettiol et al., 2017; Panova and Hilletofth, 2017). Steps (3) – (4) are argued to be especially resource-consuming, thus resulting in opportunity costs (Boffelli et al., 2018, 2020). Therefore, to increase the effectiveness of the decision-making process, we propose that initial screening tools should be used in the nascent steps of the decision-making process to eliminate inappropriate reshoring opportunities (Figure 1).

The initial screening tools are considered as those tools that provide the decision-maker with a way of avoiding unnecessary and costly reshoring options that are most likely not beneficial for the company. The need for initial screening arises from the fact that the decision-making process consumes a significant amount of the company’s resources, particularly the involvement of various managerial roles in different stages of the process (Moretto et al., 2020). Furthermore, the decision-making process needs to account for “selective reshoring” which indicate a degree of extent of the activities that needs to be brought back (Baraldi et al., 2018). The decision-making process also involves a governance decision (outsourcing or insourcing), which exacerbates its complexity (Bals et al., 2016; Barbieri et al., 2018). All these activities consume resources in the decision-making process. Therefore, the initial screening tools assist managers in making decisions on whether or not to allocate resources in the first place. The initial screening tools eliminate those reshoring alternatives that do not require further attention from the decision-maker, allowing the decision-maker to concentrate on a smaller set of solutions (Chen et al., 2008). Based on the reshoring decision-making process, it is further proposed that the initial screening tools be used while obtaining information on possible reshoring alternatives. Thus, initial screening tools are beneficial to eliminate uninteresting reshoring alternatives without wasting additional resources. Possible examples of initial screening tools for reshoring are checklists of criteria (Kinkel and Maloca, 2009; Sequeira and Hilletofth, 2019c), fuzzy inference system (Hilletofth et al., 2019b), make-or-buy comparison (Gylling et al., 2015), or other more advanced tools.

Some advanced tools for reshoring decisions have been developed originating from previous offshoring decisions. For example, a new total-landed-cost model was developed for the reshoring decision domain by applying learnings from a previous cost model used for the offshoring decision (Gylling et al., 2015). This model can make a cost-based decision whereby the case company was able to increase its savings through reshoring. However, a need to consider holistic factors has been proposed due to the bounded rationality nature of reshoring decision-making (Boffelli et al., 2020; Ciabuschi et al., 2019; Gray et al., 2017). Therefore, another advanced tool based on a fuzzy inference system was developed to support the reshoring decision-making process in a linguistic manner instead of a numerical
manner which is usually the case (Hilletoft et al., 2019b). The tool, based on fuzzy logic, provides an immediate evaluation of various input values for the different reshoring criteria. The tool was developed using facts and heuristics from experts in the reshoring domain. Six holistic criteria were considered: cost, quality, time, flexibility, innovation, and sustainability. The tool automatically evaluated a reshoring decision based on the six criteria (Hilletoft et al., 2019a). Notably, some AHP-based tools have been developed for reshoring decisions that apply traditional AHP (Sarder et al., 2014; Sequeira and Hilletoft, 2019b) and fuzzy-AHP (Pal et al., 2018a; Sequeira and Hilletoft, 2019a; White and Borchers, 2016). It has been suggested that these kinds of tools should apply a wide set of criteria (Sarder et al., 2014).

2.2 Analytical hierarchy process
The AHP, proposed by Saaty (1980), is a popular MCDM method that has a potentially wide range of applications for various problems related to decisions within the operations management domain (Emrouznejad and Marra, 2017; Ho and Ma, 2018; Subramanian and Ramanathan, 2012). The AHP has several advantages over other MCDM methods, such as hierarchical modeling of criteria and the ability to combine qualitative and quantitative criteria. Consequently, the AHP appears to be an adequate method for decision support related to reshoring decisions that use both qualitative and quantitative criteria. Typically, AHP comprises several key steps. In the first step, the decision-makers select the quantitative and qualitative criteria and layer them into a hierarchy, thereby breaking down the complex problem (Saaty, 1980, 2013; Vaidya and Kumar, 2006). Next, the decision-makers compare each criterion with all the other criteria on the same level in a pairwise manner in accordance with Saaty’s scale (Saaty, 1980, 2013). Then, a consistency ratio (CR) for each pairwise comparison is calculated. The CR acts as a thermometer for the decision-makers to ascertain whether their comparisons are consistent or not (Wang et al., 2004). In the final step, the AHP method is accompanied by a sensitivity analysis which enhances the overall quality (Borgonovo and Pischke, 2016). The sensitivity analysis helps to understand the stability of the weights of the criteria.

Despite being a feasible decision support tool, the AHP is not impervious to some shortcomings. For example, the AHP is unable to handle fuzziness or any kind of uncertainty in the data (van Laarhoven and Pedrycz, 1983; Leung and Cao, 2000). From a reshoring perspective, some factors can possess high uncertainty over time (Tate et al., 2014). Fuzzy-AHP is therefore introduced as a method to mathematically handle uncertainty and vagueness by implementing the fuzzy set theory, which is an extension to natural set theory and can be applied to the decision-making domain when considering imprecision and vagueness (Zadeh, 1965). The fuzzy set theory is the second most used decision-making method after traditional AHP (Ho, 2008; Liu et al., 2020; Mardani et al., 2015). The reason for implementing fuzzy-AHP is because crisp numbers cannot fully express decision-makers’ judgments of qualitative comparisons. Such judgments are represented by different mathematical distributions of the fuzzy sets. When fuzzy sets are used, the procedure to compute the weights is different from that of the traditional AHP method. Therefore, an extended approach was introduced in the development of the fuzzy-AHP method (Chang, 1996). In the fuzzy-AHP, it is difficult to ensure a consistent pairwise comparison. Furthermore, establishing a pairwise comparison matrix requires \( n \times (n - 2)/2 \) judgments for \( n \) criteria present. Hence, the decision-makers’ judgments will most likely be inconsistent when the number of criteria increases. Wang et al. (2008), however, presented a method that provides consistent decision rankings from only \( n-1 \) pairwise comparisons, thus improving the consistency in the fuzzy-AHP method.
3. AHP-based support tools for initial screening of manufacturing reshoring decisions

Two AHP-based support tools have been developed to investigate their suitability for the initial screening of manufacturing reshoring decisions. The development process consists of three main steps for both AHP and fuzzy-AHP: hierarchy construction, pairwise criteria comparison, and weights calculation (Figure 2).

**Step 1: hierarchy construction**

To develop the AHP-support tools for initial screening of manufacturing reshoring decisions, reshoring criteria need to be defined. There are several different ways of defining the criteria, such as literature reviews or a Delphi study with experts (Pal et al., 2018b). In this study, the criteria have been identified based on the reviews pertaining to reshoring drivers, enablers, and barriers (Barbieri et al., 2018; Wiesmann et al., 2017). The criteria can be grouped based on the following competitive priorities that have been addressed in the extant literature: cost, quality, time, flexibility, innovation, and sustainability (Sansone et al., 2017, 2020). The references that led to the selection of these criteria are shown in the table (Table 1).

The six high-level and holistic criteria were structured in the form of a hierarchy (Figure 3). In this hierarchy, the first criterion is “cost”, which is an aggregation of cost, resource, and flow efficiency. Meanwhile, the second criterion is “quality”, which comprises the quality of the product, process, and operations (Robinson and Hsieh, 2016; Di Mauro et al., 2018). The third criterion is “time”, consisting of lead time and time to market (Stentoft et al., 2016b), whereas the fourth criterion is “flexibility”, which is the ability to incorporate changes within operations. This includes how quickly a company can respond to changes in demand and customization (Gray et al., 2017; Zhai et al., 2016). The fifth criterion is “innovation”, which represents the company’s ability to be innovative regarding products, processes, or supply chains (Ancarani et al., 2016).
The sixth and final criterion is “sustainability”, which signifies the company’s ability to have sustainable operations (Ashby, 2016; Fratocchi and Di Stefano, 2019). These criteria are relevant for the initial screening of reshoring decisions because they are used to assess competitiveness at any manufacturing location (Hilletoft et al., 2019b). The output of the decision support tool will lead to a course of action, whether to further evaluate reshoring or not (Figure 3). The first alternative implies that a detailed investigation of the reshoring decision situation needs to be pursued, while the second alternative means that no such investigation is necessary.

**Step 2: pairwise criteria comparison**

A panel of eight industry experts compared and evaluated the six main criteria. The chosen industry experts comprise of the management team from a manufacturing company located in Sweden. The company manufactures various types of forklifts. The Swedish plant oversees the final assembly of the forklifts. Recently, the company has reshored some of the component manufacturing back to Sweden to improve lead-time and flexibility. This type of decision is referred to as ‘reshoring for insourcing’ (Gray et al., 2013).

<table>
<thead>
<tr>
<th>No.</th>
<th>Criteria</th>
<th>Selected references</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.</td>
<td>Time</td>
<td>Bals et al. (2016), Gray et al. (2017); Joubioux and Vanpoucke (2016); Stentoft et al. (2016b); Tate et al. (2014)</td>
</tr>
<tr>
<td>4.</td>
<td>Flexibility</td>
<td>Gray et al. (2017), Gylling et al. (2015); Stentoft et al. (2016a); Zhai et al. (2016)</td>
</tr>
</tbody>
</table>
chosen group of experts handles the reshoring decisions in the company. The experts made
an overall comparison of the criteria based on their previous reshoring experience. The
criteria comparison was made during a workshop where the experts were physically
present, and an average value of their comparisons was considered. All the involved experts
concurred that the competitive priorities criteria are a relevant group of criteria to be
considered for the development of a decision-making tool for initial screening purposes.
According to the involved experts, the relative importance of the criteria may differ in
various situations. For example, different companies could assign different degrees of
importance to the criteria in general or based on a specific product.

Next, the overall comparisons of the experts were translated into pairwise comparisons
using Saaty’s scale (Saaty, 1980, 2013). The pairwise comparison was made in two different
ways for the AHP and the fuzzy-AHP respectively. The first one used crisp values, while the
second used fuzzy values (Table 2).

These values are used to express the experts’ preferences (Routroy and Pradhan, 2013).
The allocation of integers is made in the following manner: for example, if ‘quality’ is
moderately preferred over ‘cost’, then either a crisp value 3 or a triangular fuzzy value (1, 3,
5) is entered in the corresponding row and column for the AHP and fuzzy-AHP. This, in
turn, leads to a pairwise matrix (A) represented as:

\[
A = \begin{pmatrix}
    a_{11} & \cdots & a_{1n} \\
    \vdots & \ddots & \vdots \\
    a_{n1} & \cdots & a_{nn}
\end{pmatrix}, \quad \text{and } a_{ij} = 1 \text{ if } i = j
\]

**Step 3: weights calculation**

For the AHP, the matrix is normalized for \( n \) criteria and the resulting weighted normalized
matrix (N) is denoted by the following equation:

\[
N = \begin{pmatrix}
    w_{11} & \cdots & w_{1n} \\
    \vdots & \ddots & \vdots \\
    w_{n1} & \cdots & w_{nn}
\end{pmatrix}, \quad \text{where } w_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}
\]

The term \( \sum_{i=1}^{n} a_{ij} \) is the sum of each column. Next, the weights \( w_i \) are calculated by the
equation:

\[
w_i = \frac{\sum_{j=1}^{n} w_{ij}}{n}
\]

<table>
<thead>
<tr>
<th>Crisp value</th>
<th>Fuzzy values</th>
<th>Verbal interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,1,1</td>
<td>Equal preference</td>
</tr>
<tr>
<td>3</td>
<td>1,3,5</td>
<td>Moderate preference</td>
</tr>
<tr>
<td>5</td>
<td>3,5,7</td>
<td>Strong preference</td>
</tr>
<tr>
<td>7</td>
<td>5,7,9</td>
<td>Very strong preference</td>
</tr>
<tr>
<td>9</td>
<td>9,9,9</td>
<td>Extremely strong preference</td>
</tr>
</tbody>
</table>

Table 2. Scale of preference of two criteria
Thereafter, the consistency ratio (CR) is calculated as a ratio of consistency index (CI) to random index (RI), and is represented by the following equation:

\[
CR = \frac{CI}{RI}
\]

As a standard value depending on the number of criteria, the RI value is obtained from the table below (Table 3).

An extended approach is used for the fuzzy-AHP (Chang, 1996). In this approach, first the extent analysis values for each criterion with respect to each decision alternative are obtained. For a given set of criteria \(X = \{x_1, x_2, \ldots, x_n\}\) and a set of \(m\) decision alternatives, the extent analysis values are represented by \(M_1^1, M_2^1, \ldots, M_m^1\) (where \(i = 1, 2, \ldots, n\)). All of the \(M_j^i\) (where \(j = 1, 2, \ldots, m\)) are triangular fuzzy numbers. Next, the fuzzy synthetic set \(S_i\) is defined by:

\[
S_i = \sum_{j=1}^{m} M_j^i \otimes \left[ \sum_{i=1}^{n} \sum_{j=1}^{m} M_j^i \right]^{-1}
\]

The degree of possibility for \(M_1 \geq M_2\) is defined by:

\[
V(M_1 \geq M_2) = \sup_{x \geq y} [\min(M_1(x), M_2(y))]
\]

When a pair \((x, y)\) exists such as \(x \geq y\) and \(M_1(x) = M_2(y)\), we then have \(V(M_1 \geq M_2) = 1\), otherwise,

\[
V(M_1 \geq M_2) = \frac{hgt(M_1 \cap M_2)}{(m_2 - u_2) - (m_1 - l_1)},
\]

In the above equation, \((l_i, m_i, u_i)\) and \((l_2, m_2, u_2)\) are lower, middle and upper values of \(M_i\), and \(M_2\) respectively. The values \(V(M_1 \geq M_2)\) are normalized to obtain the final priority weights.

The resulting weights from AHP and fuzzy-AHP are used to evaluate the reshoring scenarios using a weighted sum technique to arrive at an output from the AHP and fuzzy-AHP using the following equation:

\[
O_1 = \sum_{i=1}^{n} x_i w_i
\]

Table 3.

<table>
<thead>
<tr>
<th>No. of criteria (n)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random inconsistency (RI)</td>
<td>0</td>
<td>0</td>
<td>0.58</td>
<td>0.9</td>
<td>1.12</td>
<td>1.24</td>
<td>1.32</td>
<td>1.41</td>
<td>1.45</td>
<td>1.49</td>
</tr>
</tbody>
</table>

(Table 3, Average random inconsistency index based on number of criteria (Saaty, 1980))
In the above equation, $O_1$ denotes the output of either AHP or fuzzy-AHP, $x_i$ signifies the value of the criteria in the reshoring scenario, $w_i$ is the weight of the criteria from either AHP or fuzzy-AHP.

4. Results
The following section presents the results concerning the priority weights obtained for both AHP and fuzzy-AHP, the output of the evaluation of the manufacturing reshoring scenarios, and the output from the sensitivity analysis.

4.1 Priority weights
For the AHP, the result of the pairwise comparison of the reshoring criteria is shown in Table 4, whereas a normalized matrix is presented in Table 5. As per the priority weights, “quality” has the highest weight (0.41), followed by “cost” (0.29). Meanwhile, “sustainability” has the lowest weight (0.03). Finally, the value of the CR is calculated to be 0.069, which is within the acceptable limit of 0.1 (Saaty, 1980).

For the fuzzy-AHP, the result of the pairwise comparison of the reshoring criteria is shown in Table 6. The values of $L_i$, $M_i$, and $U_i$ for a criterion are computed by adding the corresponding lower, middle, and upper values across the row. This process is repeated for each of the six criteria and summed along the column $L_i$, $M_i$, and $U_i$. Next, the fuzzy synthetic set ($S_i$) and degrees of possibility are calculated and summarized (Table 7). These values are normalized to obtain the final weighted matrix (Table 8). According to the priority weights, “quality” has the highest weight (0.41), “cost” is second (0.38), while “sustainability” has zero weight.

4.2 Scenario evaluation
The priority weights from the AHP and fuzzy-AHP methods are applied to 20 reshoring scenarios (Table 9). A reshoring scenario consists of six input values $X = \{x_1, x_2, x_3, x_4, x_5, x_6\}$. The results are summarized in Table 9, where the final weights are calculated by normalizing the priorities from Table 8. The maximum value of the CR for Table 9 is 0.08, which is below the acceptable limit of 0.1 (Saaty, 1980).

Table 4.
Pairwise comparison of criteria

<table>
<thead>
<tr>
<th>Criteria (xi)</th>
<th>Cost</th>
<th>Quality</th>
<th>Time</th>
<th>Flexibility</th>
<th>Innovation</th>
<th>Sustainability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>1</td>
<td>1/3</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Quality</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>Time</td>
<td>1/5</td>
<td>1/5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Flexibility</td>
<td>1/5</td>
<td>1/5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Innovation</td>
<td>1/5</td>
<td>1/5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Sustainability</td>
<td>1/7</td>
<td>1/7</td>
<td>1/5</td>
<td>1/5</td>
<td>1/5</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.
Normalized table and final weights

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Cost</th>
<th>Quality</th>
<th>Time</th>
<th>Flexibility</th>
<th>Innovation</th>
<th>Sustainability</th>
<th>Final weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>0.21</td>
<td>0.16</td>
<td>0.38</td>
<td>0.38</td>
<td>0.38</td>
<td>0.23</td>
<td>0.29</td>
</tr>
<tr>
<td>Quality</td>
<td>0.63</td>
<td>0.48</td>
<td>0.38</td>
<td>0.38</td>
<td>0.38</td>
<td>0.23</td>
<td>0.41</td>
</tr>
<tr>
<td>Time</td>
<td>0.04</td>
<td>0.10</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.17</td>
<td>0.09</td>
</tr>
<tr>
<td>Flexibility</td>
<td>0.04</td>
<td>0.10</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.17</td>
<td>0.09</td>
</tr>
<tr>
<td>Innovation</td>
<td>0.04</td>
<td>0.10</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
<td>0.17</td>
<td>0.09</td>
</tr>
<tr>
<td>Sustainability</td>
<td>0.03</td>
<td>0.07</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Note: $\lambda_{max} = 6.43; CR = 0.069$
<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>Quality</th>
<th>Time</th>
<th>Flexibility</th>
<th>Innovation</th>
<th>Sustain-ability</th>
<th>$L_i$</th>
<th>$M_i$</th>
<th>$U_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>(1,1,1)</td>
<td>(1/5,1/3,1)</td>
<td>(3,5,7)</td>
<td>(3,5,7)</td>
<td>(5,7,9)</td>
<td></td>
<td>15.2</td>
<td>23.3</td>
<td>32</td>
</tr>
<tr>
<td>Quality</td>
<td>(1,3,5)</td>
<td>(1,1,1)</td>
<td>(3,5,7)</td>
<td>(3,5,7)</td>
<td>(5,7,9)</td>
<td></td>
<td>16</td>
<td>26</td>
<td>36</td>
</tr>
<tr>
<td>Time</td>
<td>(1/7,1/5,1/3)</td>
<td>(1/7,1/5,1/3)</td>
<td>(1,1,1)</td>
<td>(1,1,1)</td>
<td>(3,5,7)</td>
<td></td>
<td>6.2</td>
<td>8.4</td>
<td>10.6</td>
</tr>
<tr>
<td>Flexibility</td>
<td>(1/7,1/5,1/3)</td>
<td>(1/7,1/5,1/3)</td>
<td>(1,1,1)</td>
<td>(1,1,1)</td>
<td>(3,5,7)</td>
<td></td>
<td>6.2</td>
<td>8.4</td>
<td>10.6</td>
</tr>
<tr>
<td>Innovation</td>
<td>(1/7,1/5,1/3)</td>
<td>(1/7,1/5,1/3)</td>
<td>(1,1,1)</td>
<td>(1,1,1)</td>
<td>(3,5,7)</td>
<td></td>
<td>6.2</td>
<td>8.4</td>
<td>10.6</td>
</tr>
<tr>
<td>Sustain-ability</td>
<td>(1/9,1/7,1/5)</td>
<td>(1/9,1/7,1/5)</td>
<td>(1/7,1/5,1/3)</td>
<td>(1/7,1/5,1/3)</td>
<td>(1,1,1)</td>
<td></td>
<td>1.6</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>51.7</td>
<td>76.4</td>
<td>102.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Pairwise comparison using fuzzy sets.
representing the six reshoring criteria presented in section 3. The input values range from $-5$ to $+5$, where a value of $-5$ indicates that reshoring will have an extremely negative impact on the criterion. Similarly, a value of $+5$ indicates that reshoring will have an extremely positive impact on the criterion. Additionally, the value 0 indicates that reshoring would have no impact on the criterion. A total of twenty reshoring scenarios were defined based on realistic reshoring situations. The industry experts were asked to share their views on how the scenarios would be evaluated in a realistic reshoring decision situation. The output values also range from $-5$ to $+5$, where all values between $-5$ and 0 are assigned the output recommendation ‘Do not evaluate’, while values above 0 are assigned the output recommendation ‘Evaluate’. The outputs from both the AHP decision support tool ($O_1$) and the fuzzy-AHP decision support tool ($O_2$) are calculated as a weighted sum, before being compared to evaluate whether there exists any noticeable difference between the two tools. Thereafter, the difference in outputs between the two tools is measured as an absolute error (e). The mean absolute error (MAE) between the tools is also calculated for the twenty scenarios (Table 10).

For instance, in the first reshoring scenario (Table 9), the cost criterion will be extremely negatively impacted, whereas the quality, time, flexibility and innovation criteria will be slightly negatively impacted. In contrast, the (social) sustainability criterion will be positively impacted (e.g. a case in which reshoring of the component becomes a labor-intensive process). After examining this scenario, the involved experts confidently agreed that this scenario is not interesting to further evaluate. The developed decision support tools indicate a similar decision, albeit with a lower value than the experts. In another instance, in the ninth reshoring scenario, all the criteria except for sustainability, are positively impacted (e.g. a case in which reshoring the component would increase carbon emissions in the manufacturing process). The involved experts confidently agreed that this scenario is interesting to pursue reshoring. A similar decision was suggested by the developed support tools, albeit with a lower value than the industry experts. Other scenarios can be interpreted from the table in a similar manner.

The results indicate that there exists some level of agreement in the decisions between the AHP and the fuzzy-AHP tools. Out of the 20 scenarios, 18 of them provided the same

| $S_1 \geq S_2$ | 0.93  | $S_2 \geq S_3$ | 1  | $S_3 \geq S_4$ | 0.23  | $S_4 \geq S_5$ | 0.23  | $S_5 \geq S_6$ | 0.23  | $S_6 \geq S_1$ | 0  |
| $S_1 \geq S_3$ | 1  | $S_2 \geq S_4$ | 1  | $S_3 \geq S_5$ | 0.18  | $S_4 \geq S_6$ | 0.18  | $S_5 \geq S_2$ | 0.18  | $S_6 \geq S_1$ | 0  |
| $S_1 \geq S_4$ | 1  | $S_2 \geq S_5$ | 1  | $S_3 \geq S_6$ | 1  | $S_4 \geq S_1$ | 1  | $S_5 \geq S_3$ | 1  | $S_6 \geq S_2$ | 0  |
| $S_1 \geq S_5$ | 1  | $S_2 \geq S_6$ | 1  | $S_3 \geq S_1$ | 1  | $S_4 \geq S_2$ | 1  | $S_5 \geq S_4$ | 1  | $S_6 \geq S_3$ | 0  |
| $S_1 \geq S_6$ | 1  | $S_2 \geq S_1$ | 1  | $S_3 \geq S_5$ | 1  | $S_4 \geq S_3$ | 1  | $S_5 \geq S_6$ | 1  | $S_6 \geq S_5$ | 0  |

For example, in the first reshoring scenario (Table 9), the cost criterion will be extremely negatively impacted, whereas the quality, time, flexibility and innovation criteria will be slightly negatively impacted. In contrast, the (social) sustainability criterion will be positively impacted (e.g. a case in which reshoring the component becomes a labor-intensive process). After examining this scenario, the involved experts confidently agreed that this scenario is not interesting to further evaluate. The developed decision support tools indicate a similar decision, albeit with a lower value than the experts. In another instance, in the ninth reshoring scenario, all the criteria except for sustainability, are positively impacted (e.g. a case in which reshoring the component would increase carbon emissions in the manufacturing process). The involved experts confidently agreed that this scenario is interesting to pursue reshoring. A similar decision was suggested by the developed support tools, albeit with a lower value than the industry experts. Other scenarios can be interpreted from the table in a similar manner.

The results indicate that there exists some level of agreement in the decisions between the AHP and the fuzzy-AHP tools. Out of the 20 scenarios, 18 of them provided the same

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight vector</th>
<th>Final weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>0.93</td>
<td>0.38</td>
</tr>
<tr>
<td>Quality</td>
<td>1.00</td>
<td>0.41</td>
</tr>
<tr>
<td>Time</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td>Flexibility</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td>Innovation</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td>Sustainability</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

| Degree of possibility     | Minimum       | 0.93          | 1  | 0.18 | 0.18 | 0.18 | 0  |

Table 7.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight vector</th>
<th>Final weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>0.93</td>
<td>0.38</td>
</tr>
<tr>
<td>Quality</td>
<td>1.00</td>
<td>0.41</td>
</tr>
<tr>
<td>Time</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td>Flexibility</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td>Innovation</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td>Sustainability</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 8.
<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Cost</th>
<th>Quality</th>
<th>Time</th>
<th>Flexibility</th>
<th>Innovation</th>
<th>Sustainability</th>
<th>Expert opinion</th>
<th>AHP output (O₁)</th>
<th>Decision from AHP</th>
<th>Fuzzy-AHP output (O₂)</th>
<th>Decision from fuzzy-AHP</th>
<th>Absolute error e</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-5</td>
<td>-1</td>
<td>-3</td>
<td>-2</td>
<td>-3</td>
<td>3</td>
<td>-5</td>
<td>-2.49</td>
<td>Do not evaluate</td>
<td>-2.87</td>
<td>Do not evaluate</td>
<td>0.38</td>
</tr>
<tr>
<td>2</td>
<td>-2</td>
<td>5</td>
<td>-1</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>3.21</td>
<td>Evaluate</td>
<td>3.22</td>
<td>Evaluate</td>
<td>0.01</td>
</tr>
<tr>
<td>3</td>
<td>-3</td>
<td>-4</td>
<td>-3</td>
<td>-1</td>
<td>4</td>
<td>-1</td>
<td>-4</td>
<td>-2.56</td>
<td>Do not evaluate</td>
<td>-2.75</td>
<td>Do not evaluate</td>
<td>0.19</td>
</tr>
<tr>
<td>4</td>
<td>-1</td>
<td>-4</td>
<td>-1</td>
<td>-3</td>
<td>-5</td>
<td>-3</td>
<td>-4</td>
<td>-1.67</td>
<td>Do not evaluate</td>
<td>-1.14</td>
<td>Do not evaluate</td>
<td>0.53</td>
</tr>
<tr>
<td>5</td>
<td>-4</td>
<td>-2</td>
<td>5</td>
<td>-1</td>
<td>-1</td>
<td>5</td>
<td>-4</td>
<td>-1.57</td>
<td>Do not evaluate</td>
<td>-2.10</td>
<td>Do not evaluate</td>
<td>0.53</td>
</tr>
<tr>
<td>6</td>
<td>-4</td>
<td>2</td>
<td>-4</td>
<td>2</td>
<td>2</td>
<td>-5</td>
<td>4</td>
<td>1.84</td>
<td>Evaluate</td>
<td>2.32</td>
<td>Evaluate</td>
<td>0.48</td>
</tr>
<tr>
<td>7</td>
<td>-4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>0.26</td>
<td>Evaluate</td>
<td>-0.34a</td>
<td>Do not evaluate</td>
<td>0.60</td>
</tr>
<tr>
<td>8</td>
<td>-2</td>
<td>-1</td>
<td>3</td>
<td>-1</td>
<td>1</td>
<td>5</td>
<td>3</td>
<td>0.58</td>
<td>Evaluate</td>
<td>0.57</td>
<td>Evaluate</td>
<td>0.01</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>-3</td>
<td>5</td>
<td>3.92</td>
<td>Evaluate</td>
<td>4.03</td>
<td>Evaluate</td>
<td>0.11</td>
</tr>
<tr>
<td>10</td>
<td>-3</td>
<td>-5</td>
<td>3</td>
<td>-2</td>
<td>5</td>
<td>-2</td>
<td>-4</td>
<td>-2.47</td>
<td>Do not evaluate</td>
<td>-2.73</td>
<td>Do not evaluate</td>
<td>0.26</td>
</tr>
<tr>
<td>11</td>
<td>-3</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>-3</td>
<td>4</td>
<td>2.26</td>
<td>Evaluate</td>
<td>1.84</td>
<td>Evaluate</td>
<td>0.42</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>-5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>-1.66a</td>
<td>Do not evaluate</td>
<td>-1.43a</td>
<td>Do not evaluate</td>
<td>0.23</td>
</tr>
<tr>
<td>13</td>
<td>-5</td>
<td>1</td>
<td>-5</td>
<td>-5</td>
<td>-5</td>
<td>1</td>
<td>-3</td>
<td>-2.34</td>
<td>Do not evaluate</td>
<td>-2.57</td>
<td>Do not evaluate</td>
<td>0.23</td>
</tr>
<tr>
<td>14</td>
<td>-5</td>
<td>-1</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>-1</td>
<td>3</td>
<td>2.34</td>
<td>Evaluate</td>
<td>2.57</td>
<td>Evaluate</td>
<td>0.23</td>
</tr>
<tr>
<td>15</td>
<td>-1</td>
<td>5</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>5</td>
<td>-3</td>
<td>1.66⁸</td>
<td>Evaluate</td>
<td>1.43⁸</td>
<td>Evaluate</td>
<td>0.23</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
<td>Evaluate</td>
<td>0.00</td>
<td>Do not evaluate</td>
<td>0.00</td>
</tr>
<tr>
<td>17</td>
<td>3</td>
<td>-4</td>
<td>2</td>
<td>-2</td>
<td>-2</td>
<td>2</td>
<td>-3</td>
<td>-0.90</td>
<td>Do not evaluate</td>
<td>-0.66</td>
<td>Do not evaluate</td>
<td>0.24</td>
</tr>
<tr>
<td>18</td>
<td>-5</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>-0.18a</td>
<td>Do not evaluate</td>
<td>-0.94a</td>
<td>Do not evaluate</td>
<td>0.76</td>
</tr>
<tr>
<td>19</td>
<td>-5</td>
<td>4</td>
<td>2</td>
<td>-1</td>
<td>4</td>
<td>3</td>
<td>-3</td>
<td>0.03a</td>
<td>Evaluate</td>
<td>-0.48</td>
<td>Do not evaluate</td>
<td>0.51</td>
</tr>
<tr>
<td>20</td>
<td>-2</td>
<td>-5</td>
<td>-5</td>
<td>-2</td>
<td>-5</td>
<td>5</td>
<td>-5</td>
<td>-3.37</td>
<td>Do not evaluate</td>
<td>-3.65</td>
<td>Do not evaluate</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Note: ⁸Conflict in decision between output from the tool and the experts
decision. The remaining two scenarios (scenarios 7 and 19) provided conflicting decisions from the two tools. For these two scenarios, the absolute error (e) between the AHP and fuzzy-AHP is 0.6 and 0.51, respectively. The errors between the two outputs are small when compared with the range of the output (that is, $-5$ to $+5$). Outputs that are close to zero suggest a weak decision in both the support tools.

When the outputs from the AHP are compared with the experts’ recommendations, four of the decisions stemming from the tool are found to conflict with the experts’ recommendations. The conflicting decisions were observed for scenarios 12, 15, 18 and 19. Also, when comparing the outputs from the fuzzy-AHP with the experts’ recommendations, four of the decisions are observed to be inconsistent. The conflicting decisions were observed for scenarios 7, 12, 15 and 18. When cross-comparing the errors between the experts, AHP and fuzzy-AHP, the following can be observed (Table 10).

### 4.3 Sensitivity analysis

In this paper, cost and quality emerge as the most important criteria when it comes to manufacturing reshoring decisions. This is consistent with the results from previous studies that indicate that cost, but especially quality, are important to companies in high-cost countries (Engström et al., 2018a, 2018b). The presented decision support tools involved subjective judgments, which creates a risk of altering the order of importance of the criteria (Moktadir et al., 2018). Consequently, it is paramount to comprehend the manner in which even small changes in the weight of one criterion may cause a relative change in the weights of the other criteria. Sensitivity analysis is thus applied to examine the stability of the ranking of the criteria when subject to small changes (Chang et al., 2007). A sensitivity analysis is performed for the two most influential reshoring criteria, namely, cost and quality, for the AHP and the fuzzy-AHP. The criterion cost is incremented in steps of 0.1 in its priority weight, after which the corresponding changes in the priority weights of the other criteria are recorded (Figure 4). Next, the criterion quality is incremented in steps of 0.1 and the corresponding changes in the weights of the other criteria are recorded (Figure 5). In both figures, the lines for the criteria time, flexibility, and innovation overlap indicating that their priority weights are the same. A similar behavior was observed for fuzzy-AHP, the major difference being that the sustainability criterion obtained zero priority weight for all combinations of values for cost and quality.

In Figure 4, when the priority weight of the cost criterion increases, the criteria cost and quality switch position in their importance. At high values for the priority weights of cost, the sustainability criterion slowly reduces its priority weight to zero. This implies that for high values of cost or quality, the decision is mainly driven by the input values of cost and quality. Any uncertainty or change caused by internal or external events or other criteria will not have any effect on the decision. On the other hand, for low values of priority weight of cost, other criteria, such as time, flexibility, and innovation switch their level of importance. This means that the order of importance is unstable for low values of cost and quality (between 0.3 and 0.4). For these values of cost and quality, any uncertainty or change induced by internal/external events or other criteria will have an impact on the decision.

### Table 10.

<table>
<thead>
<tr>
<th>Comparison in error</th>
<th>Mean absolute error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between expert’s opinion and AHP</td>
<td>2.28</td>
</tr>
<tr>
<td>Between expert’s opinion and fuzzy-AHP</td>
<td>2.23</td>
</tr>
<tr>
<td>Between AHP and fuzzy-AHP</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Similar observations were made when the quality criterion was incrementally increased or decreased.

5. Discussion
The decision-making process of manufacturing reshoring has not yet been extensively studied due to the novelty of the phenomenon (Barbieri et al., 2018; Stentoft et al., 2016a). So far, limited studies have been carried out on AHP-based support tools for the decision-making process relating to manufacturing reshoring (Pal et al., 2018a; Sarder et al., 2014; Sequeira and Hilletofth, 2019a, 2019b; White and Borchers, 2016), whereas nearby domains, such as supplier selection and evaluation, have, to a large extent, taken advantage of a multitude of decision support tools (Emrouznejad and Marra, 2017; Vaidya and Kumar,
Consequently, complex reshoring decisions necessitate the development of more tools to support the decision-making process. An interesting avenue to follow for the purpose of developing decision support tools concerning complex reshoring decision-making is related to initial screening. An initial screening tool eliminates uninteresting reshoring alternatives and allows the decision-maker to concentrate on a limited set of solutions (Chen et al., 2008). Such a tool is used to signal to the decision-makers not to invest time and resources on unpromising reshoring activities, and therefore, to end the decision-making process early. This study investigates support tools for the initial screening of manufacturing reshoring decisions. Two methods have been previously explored in the context of manufacturing reshoring decision-making: AHP (Sarder et al., 2014) and fuzzy-AHP (Pal et al., 2018a; White and Borchers, 2016). However, further research on these methods is still required (Sarder et al., 2014). Therefore, two tools based on the AHP and fuzzy-AHP were explored for initial screening of manufacturing reshoring decisions by applying twenty different reshoring scenarios. The results indicate that the differences between both these tools are negligible, as evidenced by the presented MAE values. This suggests that both tools behave similarly on a high level. This observation was also confirmed by the sensitivity analysis.

When comparing the AHP and fuzzy-AHP tools, different priority weights have been obtained for the reshoring criteria, although the differences are not significant. One of the less important criteria in the AHP evaluation, sustainability, received a zero-priority weight in the fuzzy-AHP evaluation. This suggests that during uncertainty, it is possible that some of the criteria receive zero weights, thus implying that they will not be considered in a decision (Wang et al., 2008). Furthermore, the criteria’s order of importance did not change when incorporating fuzziness. The sensitivity analysis, however, revealed that the order of importance is likely to switch for higher priority weights for the cost and quality criteria. Regarding low priority weights for cost and quality, other criteria (time, flexibility, and innovation) are likely to switch their order of importance. When comparing the findings of this study to those of previous MCDM studies related to reshoring decision support, it is interesting to note that a similar order of importance among the criteria was observed (Sarder et al., 2014). As a case in point, quality was considered the most important criterion followed by cost (logistics cost) in the reshoring domain (Sarder et al., 2014). However, in another study, where fuzzy-AHP was used, flexibility emerged as the most important criterion followed by quality in the reshoring domain (Pal et al., 2018a). The sustainability criterion did not receive high weights and it is claimed that sustainability is often taken for granted (Pal et al., 2018a). This may partially explain why sustainability turned out to be the least important criterion in the developed decision support tools, especially for initial screening purposes. Future research needs to be directed toward incorporating sustainability objectives in decision support tools for the initial screening of manufacturing reshoring decisions.

The confidence in the decisions is indicated by the output values from the decision tools. Despite the inconsistency between the experts’ recommendation and the decision from the tools for some reshoring scenarios, the output values indicated a low confidence in these decisions. One way to mitigate the problem of low confidence is by defining multiple output values, rather than binary output values, as observed in the tools involved in this study. Comparing both tools, fuzzy-AHP was found to have a slightly lower MAE than the AHP when both were compared against the experts’ recommendations, thus indicating that fuzzy-AHP performed only slightly better. The mean error in decision is 2.28 and 2.23 for AHP and fuzzy-AHP, respectively. The size of the errors was observed to be higher than the reshoring decision support tools based on a fuzzy inference system (Hilletofth et al., 2019b). One plausible reason for this behavior is that the fuzzy inference system is more advanced.
concerning configurations, membership functions, and fuzzy rules, something that is lacking in AHP-based tools. As initial screening tools for reshoring decisions, 80% out of the twenty reshoring scenarios have been consistent with the experts’ recommendations. Therefore, it can be inferred that traditional AHP and fuzzy-AHP support tools provide satisfactory results. Regarding the generalizability of the tools, the developed tools cannot claim to be fully generalizable because the criteria were evaluated by only a limited number of industry experts. In order for these tools to be fully generalizable, the priority weights should be in agreement with those arrived at by other decision-makers through a larger sample of experts. This leads to the following propositions:

\[ P1. \] AHP and fuzzy-AHP are suitable tools for the initial screening of manufacturing reshoring decisions.

\[ P2. \] Incorporating fuzziness into the manufacturing reshoring criteria slightly enhances the accuracy of the decision.

Many existing frameworks have used the criteria originating from companies’ competitive priorities (Benstead et al., 2017; Wiesmann et al., 2017). In line with such research, this study also applied the criteria that correspond to competitive priorities. This is because competitiveness is usually highly requested by most companies. The six criteria applied in this paper are based on the recent studies conducted on competitive priorities (Hilletoft et al., 2019b; Sansone et al., 2020). The competitive priorities criteria constitute a feasible set to develop initial screening tools for manufacturing reshoring decisions. Notably, the six criteria are on a high level comparable to those used in prior AHP and fuzzy-AHP studies within the manufacturing reshoring domain (Pal et al., 2018a; Sarder et al., 2014).

The priority weights of the criteria obtained in both AHP and fuzzy-AHP were slightly different (Figure 6).

A difference was observed in the cost criterion, where an increase was observed in the weight of the criterion for the fuzzy-AHP. This suggests that when uncertainty is introduced...
in a decision, the weight of an already important criterion increases compared to the weight in AHP. Consequently, the uncertainty in decision-making will favor important criteria. In contrast, the opposite was observed among the less important criteria. The importance of the sustainability criterion, for example, was reduced to zero in the fuzzy-AHP. This, in turn, leads to important decision-making implications involving sustainability being a low weight criterion. First, the zero-weight criterion will be completely neglected in the initial screening of manufacturing reshoring decisions, which can be perceived as a disadvantage (Wang et al., 2008). It becomes a disadvantage when criteria from competitive priorities are used since one of the priorities is completely neglected in a fuzzy-AHP decision tool (that is, sustainability). This is consistent with a recent literature review, according to which “neither scholars nor firms’ managers and entrepreneurs considered the environmental and social pillars of sustainability” during reshoring decision-making (Pratocchi and Di Stefano, 2019, p. 468). A plausible reason for this assertion is that the companies that are reshoring back to high-cost countries are required to contemplate more stringent environmental and social sustainability regulations from the onset and thus, take sustainability issues for granted (Pal et al., 2018a).

To reiterate, there is a paucity of research related to sustainability and its associated impact on reshoring decisions. Also, assigning low importance to sustainability during the pairwise analysis in the fuzzy-AHP is something that needs to be further evaluated by the industry experts. As shown in this paper, incorporating uncertainty in decision-making leads to the augmentation of the weights of the more important decision criteria, while simultaneously reducing the weights of the less important decision criteria. However, this might lead to questions, such as why environmental and social sustainability reshoring criteria are still highly unexplored (Orzes and Sarkis, 2019). This leads to the following propositions:

P3. Competitive priorities criteria is a suitable group of criteria to include in the initial screening tools for manufacturing reshoring decisions.

P4. Incorporating fuzziness into manufacturing reshoring criteria augments the importance of already important criteria and reduces the importance of already unimportant criteria.

In this study, both presented tools provided an equal number of coherent decisions when compared to those of the industry experts. Out of the twenty presented reshoring scenarios, both tools provided 16 coherent decisions, thus yielding a decision reliability of 80%. This indicates that there is a scope for further improvement of the decision reliability of the tools. One way could be to explore other means of combining weights with values of criteria. For example, a weighted product technique has shown to be superior to the classical weighted-sum technique (Krejčí and Stoklasa, 2018). In previous studies, AHP and fuzzy-AHP have been used to obtain criteria weights, but they have not been used to evaluate different reshoring scenarios. Unfortunately, this means that the reliability of the decisions presented in this study cannot be compared with those reported in previous studies (Pal et al., 2018a; Sarder et al., 2014). It can also be disputed if the pairwise comparisons are situational and company-dependent and if the weights for reshoring decisions can be linked to competitive priorities in a general manner. It is for this reason that further research could bring about improvements in the decision support tools within this area. The decisions provided by the developed support tools are binary decisions, that is either ‘Evaluate’ or ‘Do not evaluate’. Furthermore, a small value is enough to switch the decisions. As a case in point, for an output value of 0.00, the decision is ‘Do not evaluate’, while for an output of 0.01 the decision is ‘Evaluate.’ Hence, a diminutive increase of only 0.01 in the output can lead to a shift in the decision, whether to evaluate reshoring or not. Therefore, and to further improve the tools’
accuracy, it would be desirable to introduce a range of “middle” decisions (for instance, strongly or weakly-recommend evaluation) containing all the non-coherent output values from the AHP and fuzzy-AHP. This leads to the following proposition:

\[ P5. \] The reliability of the traditional AHP and the fuzzy-AHP tools in manufacturing reshoring can be increased by incorporating middle decisions to complement the two extreme decisions.

Rapid changes in global competitive conditions, caused, for example, by the coronavirus pandemic, create uncertainty in decisions that needs to be factored into the decision support tools. In this study, the fuzzy-AHP tool is shown to be capable of handling uncertainty by increasing the weights of the important criteria. This emphasizes the importance of uncertainty-based decision support tools, such as the fuzzy-AHP, in manufacturing decisions. A significant step in the process is by limiting the number of criteria on a high level to reduce the complexity of the decision-making problem. The complexity is also reduced further by structuring the criteria in a hierarchy, which is the first step in simplifying the complex reshoring problem. This also makes the criteria observable to the decision-makers (Sequeira and Hilletofth, 2019c). It requires, however, the decision-makers to possess sufficient knowledge of the criteria and the relationships between them (Saaty, 1980; Vaidya and Kumar, 2006).

6. Implications for practice and society
This study has several managerial implications concerning the decision-making process when dealing with manufacturing reshoring. The first implication is that the developed AHP and fuzzy-AHP tools provide a decision-related suggestion to the managers on whether the reshoring decision-making process should be continued or not. Managers can evaluate various reshoring scenarios with the same tools and, accordingly, pursue the most promising scenario. Considering the recent findings of behavioral aspects inherent in the decision-making process (Boffelli et al., 2020), the need for fuzzy-AHP tools is paramount. Furthermore, when the complexity is high, the balance of weights of the criteria shifts toward already important criteria, such as cost and quality. Therefore, the second implication is that the managers benefit more from fuzzy-AHP than a traditional AHP when dealing with complex reshoring decisions. While making reshoring decisions, managers find themselves ambivalent as to whether they should wait for complete information or take an early decision. The presented tools guide managers to consider holistic criteria of competitiveness while providing a rapid evaluation of any possible reshoring opportunity. The holistic competitiveness criteria are regarded as a suitable starting point to evaluate reshoring opportunities. Thus, the third implication is that the managers would not have to experience an “information overload” during the initial screening of reshoring decisions as they only need to consider a few, yet holistic criteria. In this study, the criteria were weighted using pairwise comparisons. Therefore, the fourth implication is that competitiveness criteria can be suitably prioritized in a reshoring decision-making process. The potential success of the AHP method suggests the suitability of a hierarchical structure of criteria in the reshoring decision-making process. This hierarchy could be tailored to the needs of the company by incorporating company-specific sub-criteria and sub-sub-criteria. To conclude, the tools explored in this study are most beneficial to managers to avoid unnecessary and costly reshoring options.

This study also has several implications for society. Firstly, manufacturing reshoring is a part of an important economic agenda in several industrialized countries. This can be ascribed to the positive impact of the manufacturing industry on a country’s overall...
economy, particularly at a time when the ongoing pandemic has been catastrophic for the global economy at large. Therefore, as a step toward rebuilding the economy, the developed decision support tools help accelerate the reshoring decision-making process. Secondly, manufacturing reshoring can re-ignite relationships with local suppliers and help create a positive rate of employment in a region. Therefore, the developed tools have the potential to expedite these positive impacts. Thirdly, the use of a relative scale from $-5$ to $+5$ for the criteria in the developed support tools allows for simpler communication with external stakeholders (e.g. customers, suppliers, or policymakers) than absolute values (Hilletoft et al., 2019b). Furthermore, this type of scale can facilitate both rational and intuitive behavioral types of decision-making (Boffelli et al., 2020). Finally, this study contemplates the sustainability criterion in the developed decision support tools to ensure that companies do not disregard the United Nations’ sustainability goals in this process. Surprisingly, the sustainability goals seem to have been taken for granted while evaluating reshoring decisions (Pal et al., 2018a). Therefore, these goals must be explicitly communicated to society. We hope that a sustainability thinking is increasingly taken into consideration in such types of decisions.

7. Conclusion

This paper presents how decision support tools, built upon AHP and fuzzy-AHP methods, can be used for the initial screening of manufacturing reshoring decisions based on competitive priority criteria. The current literature within the reshoring domain suffers not only from a paucity of research on how manufacturing reshoring decisions are taken, but also from a limited number of support tools that enable optimal decision-making related to reshoring. Furthermore, manufacturing reshoring decisions are inherently complex and can be both time consuming and resource intensive, thus escalating the opportunity costs. An initial screening tool has the potential of eliminating uninteresting reshoring opportunities. Using this as a starting point, this study investigated the suitability of the AHP and fuzzy-AHP methods as potential tools for the initial screening of manufacturing reshoring decisions. Although both methods are well established in literature, they have not been adequately applied to the manufacturing reshoring decision-making domain. To validate the feasibility of applying the AHP and fuzzy-AHP methods in this domain, six criteria stemming from the competitive priorities area were used, since the general goal of any relocation decision should be to increase the company’s competitiveness. The six criteria were subjected to pairwise comparisons in both AHP and fuzzy-AHP by engaging a panel of industry experts on manufacturing reshoring; as a result, priority weights for the six criteria were obtained. The research presented in this paper contends that both AHP and fuzzy-AHP are suitable tools for the initial screening of manufacturing reshoring decisions. In the latter tool, the fuzziness introduced to the reshoring criteria led to a slightly better alignment between the tool and the experts’ recommendations. The fuzziness introduced also augmented the weights of already important criteria while reducing the weights of the less important criteria. The research proposes that the reliability of the tools can be improved by incorporating middle decisions in the output, since errors were detected among a small set of output values when the output lied in the middle of two extreme binary decisions. Moreover, the competitive priorities criteria observed to be suitable when developing the initial screening tools for manufacturing reshoring decisions.

For future research, the traditional AHP and fuzzy-AHP need to be applied to other types of criteria in the manufacturing reshoring domain instead of those stemming from the competitive priorities, such as specific companies’ resources, capabilities, or risks. This would make the tools more sophisticated and applicable beyond initial screening. Both
traditional AHP and fuzzy-AHP should be explored using real cases, where the collected data should be incorporated into the tools. Such explorative studies could yield interesting findings, not only with respect to the tools themselves, but also in terms of the reshoring decision-making process. Furthermore, these tools need to be explored in other manufacturing contexts with a view to increase their generalizability. Another important avenue for future research would be to investigate the role of ‘sustainability’ in reshoring research. As a matter of fact, recent calls for this type of research have already been proposed (Orzes and Sarkis, 2019). One potential reason for the low interest in sustainability might be that many sustainability issues are already legislated in many countries. Furthermore, companies might need to consider sustainability in the new location, but it is regarded more as a boundary condition (or an order qualifier) than a competitive priority. Hence, there exists an unexplored relationship between sustainability and reshoring which merits further investigation. Another future research avenue would be to explore priority weights in different types of contexts. In this study, the priority weights had the perspective of reshoring to a high-cost country; however, other contexts may entail priority weights that are dissimilar to those applied in this study, thus leading to different results.

References
Bettiol, M., Burlina, C., Chiavesio, M., Di Maria, E., (2017), “Industrial district firms do not smile: Structuring the value chain between local and global”, in Pedersen, T, Devinney, T.M., Tihanyi,


Sarder, M.D., Miller, C. and Adnan, Z. (2014), “Understanding the reshoring decision-making process using AHP approach”, In Proceedings of IIE Annual Conference Institute of Industrial and Systems Engineers (IISE), Montreral, Canada.


About the authors

Movin Sequeira (MSc) is a PhD Student at Jönköping University in Sweden. His research interest includes manufacturing relocation, expert systems, decision support and sustainable production. He has a Lic. Eng. degree in Production Systems and an MSc degree in Production Development and Management from Jönköping University, Sweden. He completed his Bachelors in Mechanical Engineering from NMAM Institute of Technology, India. He has published articles in international journals including Expert Systems with Applications and Industrial Management and Data Systems, and international peer-reviewed conferences such as EurOMA, IPSERA, OSCM and ICESDP. Movin Sequeira is the corresponding author and can be contacted at: movin.sequeira@ju.se

Per Hilletofth (PhD) is a Professor of Industrial Management at University of Gävle in Sweden. His research focuses on operations strategy, manufacturing location, supply chain design, new product development and demand and supply integration. He has published articles in international journals including International Journal of Production Economics, Supply Chain Management, Production Planning and Control, Expert Systems with Applications, Industrial Management and Data Systems, Journal of Business and Industrial Marketing, Innovation: Organization and Management, Journal of Manufacturing Technology Management and European Business Review. He has editorial assignments in several international journals.

Anders Adlemo (PhD) is an Associate Professor of Computer System Engineering at Jönköping University in Sweden. His research has a focus on fuzzy logic solutions applied to a number of application domains related to decision-making, one being the production relocation domain. He has published more than 60 papers at international peer-reviewed conferences and in international journals including Control Engineering Practice, Journal of Systems Integration, Journal of Intelligent Manufacturing, International Journal of Computer Integrated Manufacturing and Expert Systems with Applications.