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Complementarities between information sources to support the implementation of Advanced Manufacturing Technologies*

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Abstract. In the past decade, manufacturers have invested significantly in the implementation of advanced manufacturing technologies (AMT) in an attempt to reduce costs and gain a competitive advantage in their industries. The benefits of these investments in AMT have been varied, and in some cases significantly negative. To date, the impact of information supports on AMT implementations and the complementarities that exist between such supports have not been determined. This study develops a model of manufacturing plant productivity using complementarity assumptions developed by [13, 14] to identify the impact of acquiring specific sets of information supports on the implementation of AMT. In order to demonstrate the practical application of the results, the optimal information support practices are provided for a couple of example plants using a solution lattice based on results from this study.

Keywords: complementarities, implementation support, advanced manufacturing technology, supermodularity

1 Introduction

Due to the increased pressures of global competition and the current state of the global economy, there has been a continuous increase in pressure to improve efficiency in manufacturing. As a result, organizations have been introducing innovations over the past few years through the implementation of diverse forms of advanced manufacturing technologies (AMT)[22]. There are numerous alternatives to consider when selecting the types of AMT that are implemented in a particular plant including: bar-coding, computer-aided design, robotics, and automated storage and retrieval systems[1, 18]. The importance of AMT implementations continues to increase, particularly for small and medium sized plants that need the efficiencies to compete with the economies of scale available to the larger plants[11]. Based on previous empirical evidence, the impact of these implementations remains under debate[19]. For those organizations who have successfully implemented AMT, the impact has been significant[9]. Unfortunately, many AMT implementations result in little or no significant gains in productivity or profitability for the firm with the reason for such results remaining relatively unknown.

The increasing complexity and level of integration between the various types of AMT are resulting in obstacles to successful implementations[8]. This paper will attempt to identify the influence that various forms of information for the support of AMT implementations by determining complementarities that exist between these support networks and increase profitability or labour productivity of the plants. Through the understanding of complementarities, managers will be able to better understand the need to co-ordinate and participate

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in information networks for supporting the implementation of new technologies[16]. The impact of the size of the plant as well as the industry in which it operates is also examined to determine the impact of these environmental factors on the need for information supports.

The results from this study will extend current knowledge on the complementarities between organizational practices to support the successful implementation of AMT. This study will explore the impact of information support for the implementation of new complex technology systems and the differences between small and large plants in terms of a need for external support networks. The final portion of this paper will use a solution lattice to illustrate the practical application for managers of the use of complementarity results to make strategic decisions for supporting future AMT implementations. The solution lattice is created using the complementarity and substitute pairing results to ensure that plants move from an initial state on the lattice to a neighbouring state that is more beneficial. By looking at their plants position on the solution lattice, managers will be able to identify the optimal path for transitioning from their current set of practices to the optimal performing state in their size class or industry.

2 Background

Complementarity is defined as any two or more variables that demonstrate a higher marginal return to higher values in the remaining variables when any one of the variables is increased[14]. The effect of complementarity essentially means that there is a significant benefit to having business strategies or making investments in clusters. Complementarity suggests that implementing a new ”cost saving” initiative may results in the opposite effect if the new practice and the existing structure and strategies are substitutes to one another (e.g. they do not fit together and support each other). In terms of information sources for implementation support, consider source of research and development (R&D) and primary stakeholders. The benefits of R&D or primary stakeholder support might be greatly increased by implementing them together (refer to Fig. 1). In this case, R&D and primary stakeholder support would be complements.

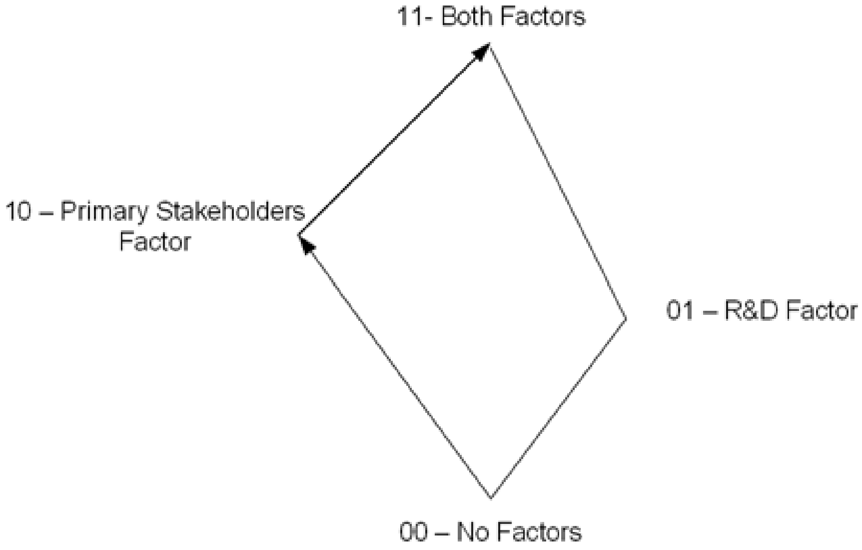

Fig. 1. Example segment of a simple solution lattice

Complementarity analysis is also used to argue that the complex set of strategies and policies used by an incumbent firm cannot be matched overnight by a new entrant into the market and therefore represent a source of competitive advantage for the firm[20]. If a plant has a complex set of complementary strategies and practices it will take a significant amount of time for the imitator to achieve the same or similar the complementary balance. Rivkin[17] also supported the argument that a competitive advantage results from the complexity due to a high level of complementarity between strategies and internal policies.

A decentralized corporate environment is typically viewed as beneficial for introducing innovation such as AMT. The premise is that if people make independent decisions, then if one person makes a poor choice then it will be offset by another's insightful decision[7]. This is not the case when complementarities are involved. Dietl[7] showed that when there are numerous complementarities, the systematic error of a centralized, coordinated system would be less costly than the random errors of a decentralized organization. The error is less costly since all of the complementary elements are still coordinated and the supermodularity of the function is being exploited even with a sub-optimal solution[14].

Mohnen and Roller[15] recently examined obstacles to innovation that could be reduced by government policies in the European Union and determined that there were significant complementarities between innovation policies. It has been shown in [14] that managers working independently, using an uncoordinated decision structure, will systematically under-respond to external uncertainties and may never establish the optimal set of organizational strategies. This is similar to the results of Cowan[5] that with the increase in technology usage the unpredictability of implementation path development can lock in the usage of inferior sets of AMT. Mohnen and Roller[15] also demonstrated that access to qualified labour, which can be improved through strong links of support with higher education institutions and external sources of support, was the primary obstacle to be overcome for an innovative environment to exist within a firm.

Through the improved understanding of complementarities and substitutes between sources of information support for the implementation of AMT managers will be better able to plan and make strategic decisions about information network development. Once the complementary and substitute sources of information support for AMT implementation are recognized, and the lattice for the industry identified, then managers will be able to identify the optimal path for investments in information networks to support AMT implementation. The optimal implementation path exemplified in the example solution lattices found in section five will identify not only which sources of implementation support will complement each other but also the importance or size of the improvement that the complementarity effect represents.

3 Methodology

This study uses Statistics Canada's Survey of Advanced Technology in Canadian Manufacturing to conduct ex post hypothesis tests pertaining to the impact (both positive and negative) of sources of implementation support on the success of AMT implementations as measured by plan profitability and labour productivity. This survey was linked to the Annual Survey of Manufactures resulting in a final sample size of 2,191 plants[3]. Although the plant industry was determined by standard industry code (SIC) due to sample size and analysis method the 2-digit SIC were grouped into 11 industries for analysis[4].

Plant size and primary industry of operation were used as controls throughout the study in order to account for some of the external environment factors impacting the dependent variables. Individual production models were created for each of three size classes of plants. Separate production models were also created for each of the eleven industries in order to reduce the potential bias due to the types of AMT implemented, existing information networks, and government support structures. The size class of the plant remained a control variable within the industry analysis.

3.1 Variable definition

Four factor variables were used to describe the sources of information to support AMT implementation used by the plants. These were derived using Maximum Likelikhood factor analysis using a promax rotation.

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[3] The food industry was not part of the target population for the Survey of Advanced Technology in Canadian Manufacturing - 1998. In addition, to reduce the burden on small businesses, only establishments with at least ten employees (according to Statistics Canada's Business Register) were considered for sample selection. The distribution by size class is 686 large plants (at least 250 employees), 1,006 medium plants (50-249 employees), and 499 small plants (fewer than 50 employees). The distribution of plants by industry is: chemical (258), electronics (218), furniture and other (187), machinery (95), metal (219), non-metals (117), plastics (133), textiles (296), vehicles (239), and wood (429).

[4] Chemical (SIC 36, and SIC 37), Electronic (SIC 33), Machinery (SIC 31), Metals (SIC 29 and SIC 30), Non-Metals (SIC 35), Plastics (SIC 15 and SIC 16), Textiles (SIC 17, SIC 18, SIC 19, and SIC 24), Vehicles (SIC 32), Wood (SIC 25, SIC 27, and SIC 28), and Furniture and Other (SIC 26 and SIC 39).

The first factor represents primary stakeholders including production engineering staff, manufacturing staff, the design teams, direct suppliers, and patents. The second factor represents support from research and development: internal research, experimental development, production engineering, trade fairs, governments, and other producers. The third factor represents support from external information sources including sales and marketing, customers, as well as related firms. The final factor represents sources of implementation support from corporate organizations such as the head office of the plant, related plants within the larger organization, and universities. The distribution of the sources of information support is unbalanced but was restricted due to modeling limitations on the matrix sparceness. The classification of the factors is also intuitive from an analysis point of view as the types of information networks represented by the factors are similar to those one would expect to find in every industry setting.

Table 1. Variance explained by information source factors

Factor	Variance Explained
1 - Primary Stakeholders (production engineering staff, manufacturing staff, design teams, direct suppliers, and patents)	37.85%
2 - Research and Development (internal research, experimental development, production engineering, trade fairs, governments, other producers)	26.99%
3 - External Information Sources (sales and marketing, customers, related firms)	24.01%
4 - Corporate Organizations (head office, related plants within organization, universities)	21.20%

Binary indicator variables I_{ij}, representing state i in industry j, were developed in order to represent the possible combinations (or states) of sources of information support for the implementation of AMT. The factor indicator was coded as 1 if the total score for the plant for the variables included in the factor were greater than the size class mean for that factor (refer to Tab. 2). This ensured that the size of the plant did not bias any of the industry specific results as the level of investment and number of sources of information support varied significantly between small and large plants. The indicator variables are defined using conventional binary algebra with each digit representing a factor listed from left to right (e.g. I_{5j} would represent state 0101, plants exhibiting both the second (R&D) and fourth (corporate organizations) factors).

Table 2. Factor means by size class.

Factor	Large Plant	Medium Plant	Small Plant
Primary Stakeholders	5.9096	4.2986	2.8610
Research and Development	3.1293	2.0230	1.0992
External Information Sources	2.9022	2.2305	1.5373
Corporate Organizations	1.9847	1.2442	0.7220

The distribution of plants based on size class reveals interesting results (refer to Tab. 3). Even after accounting for size in the definition of the indicator variables, there are significantly less small and medium sized plants exhibiting the information support factor variables that in the large plants. Only 11% of large plants do not exhibit at least one of the factor variables whereas almost 26% of medium plants and 38% of small plants do not exhibit any of the factors. There are very few plants (regardless of size) in state 6 (exhibiting only research and development (R&D) and external information sources). This may be a result of the nature of the implementations and innovations occurring in that those developed in house through internal R&D initiatives cannot easily or efficiently obtain support from external sources as they will be unfamiliar with the technology. In particular, there are no small plants at all in this particular state (note the lack of small plants in the state may also be due to the minimal number of small plants with internal R&D departments). Small plants are also quite different from their medium and large plant counterparts in state 3 (exhibiting only external information and corporate organizational sources). Less than 1% of small plants occupy state 3 whereas approximately 10% of large and medium plants occupy this state.

Table 3. Plant Distributions by Size Class*

State	Large Plant	Medium Plant	Small Plant
0 - 0000 (no factors)	11.16%	25.71%	37.71%
1 - 0001 (factor 4)	7.54%	4.56%	4.71%
2 - 0010 (factor 3)	1.62%	1.67%	1.76%
3 - 0011 (factor 3 & 4)	10.29%	9.45%	0.83%
4 - 0100 (factor 2)	1.09%	2.52%	1.22%
5 - 0101 (factor 2 & 4)	1.91%	2.03%	0.37%
6 - 0110 (factor 2 & 3)	0.34%	0.17%	0.00%
7 - 0111 (factor 2, 3 & 4)	1.13%	1.63%	0.43%
8 - 1000 (factor 1)	4.47%	5.16%	2.97%
9 - 1001 (factor 1& 4)	4.03%	1.54%	1.74%
10 - 1010 (factor 1 & 3)	4.60%	8.49%	7.83%
11 - 1011 (factor 1, 3 & 4)	14.27%	6.14%	12.72%
12 - 1100 (factor 1 & 2)	1.04%	4.81%	0.91%
13 - 1101 (factor 1, 2 & 4)	1.55%	2.22%	4.63%
14 - 1110 (factor 1, 2 & 3)	5.02%	10.75%	4.34%
15 - 1111 (all factors)	29.94%	13.14%	17.85%

*Refer to Tab. 1 for factor definitions

The distribution of plants by industry also demonstrates the need to conduct industry specific analysis (refer to Tab. 4) as none of the industries exhibit similar patterns of information network utilization. The textile industry displays a large number (over 58% of plants) in state 0 (no support factors exhibited). This may be due to the artistic nature of much of the industry where high levels of information support networks are not readily used. Only the chemical, electronic, machinery, textiles, and wood industries exhibit any plants in state 6 (R&D and external information sources). Two of these industries, textiles and machinery, exhibit no plants in state 7 though (R&D, external information, and corporate organizations). This demonstrates the industry differences in the selection of clusters of information support networks used to aid in the implementation of AMT. Other unique results include over 12% of metals plants in state 3 (external information and corporate organization sources), over 14% of wood plants in state 10 (primary stakeholders and external information sources), and over 28% of chemical, electronic, plastics, and vehicle plants present in state 15 (all factors exhibited). The large variation in the distribution of plants in the factors states supports the need for analysis at the industry level and that aggregate analysis would result in significant confounding of the results.

3.2 Constrained regression model

Typically, complementarities, particularly for discrete variables, are determined using a simple form of regression analysis[1, 3, 4]. These regression models use the correlation between variables as an indicator of complementarities and substitutes. The problem with this basic form of regression analysis, according to [15] and [2] is that when the unobservables are positively correlated, this method results in a positive bias in the estimate of the interaction effects. Thus, these approaches may find complementarities or substitutes when none exist.

This study uses a constrained regression model to determine complementarity based on lattice theory results. Lattice theory has been applied by [13, 14, 21] to economic problems in the realm of profit optimization. This theory imposes a structure to the problem of determining complementarity that allows for the use of discrete measures and variables in the optimization process, something that is not possible using conventional economic theory of elasticities. In order to determine complementarities using the constrained regression method one must demonstrate that the objective function (productivity or profitability models in this study) is supermodular in each pair of elements. To determine if the pairing is substitutes then one must demonstrate

Table 4. Plant Distributions by Industry*.

State	Chemical	Electronic	Furniture and Other	Machinery	Metals	Non-Metals	Plastics	Textiles	Vehicles	Wood
0-0000 (no factors)	38.00%	23.55%	38.70%	29.30%	23.80%	38.40%	26.31%	58.50%	23.00%	28.26%
1-0001 (factor 4)	2.71%	1.53%	1.86%	3.63%	8.43%	8.50%	4.59%	4.69%	2.79%	4.58%
2-0010 (factor 3)	0.74%	1.74%	2.66%	2.67%	0.34%	0.24%	0.08%	0.13%	1.84%	3.86%
3-0011 (factor 3&4)	0.67%	3.74%	1.59%	0.17%	12.05%	0.15%	1.87%	1.05%	2.77%	3.99%
4-0100 (factor 2)	2.64%	2.55%	2.71%	1.19%	0.64%	0.61%	0.45%	3.69%	3.78%	0.82%
5-0101 (factor 2&4)	0.74%	2.05%	0.39%	0.17%	1.07%	0.70%	1.29%	1.61%	3.69%	0.46%
6-0110 (factor 2&3)	0.13%	0.23%	0.00%	0.07%	0.00%	0.00%	0.00%	0.36%	0.00%	0.07%
7-0111 (factor2,3&4)	0.87%	0.95%	1.56%	0.00%	0.41%	2.85%	0.45%	0.00%	1.68%	1.18%
8-1000 (factor 1)	2.38%	1.46%	6.41%	7.38%	1.32%	0.55%	5.39%	2.63%	3.74%	5.33%
9-1001 (factor 1&4)	3.53%	1.81%	0.53%	0.63%	1.23%	3.37%	1.05%	3.33%	0.27%	2.69%
10-1010 (factor 1&3)	1.68%	3.90%	4.48%	8.94%	7.61%	3.46%	6.53%	7.48%	1.50%	14.67%
11-1011 (factor1,3&4)	3.92%	11.01%	8.73%	5.06%	14.30%	13.08%	6.99%	7.89%	12.78%	12.23%
12-1100 (factor 1&2)	4.46%	5.74%	4.13%	4.85%	1.00%	2.89%	3.65%	0.90%	1.69%	0.55%
13-1101 (factor1,2&4)	4.06%	1.96%	3.72%	7.06%	0.63%	3.19%	5.46%	1.42%	1.99%	6.63%
14-1110 (factor1,2&3)	5.78%	9.24%	5.95%	4.20%	14.71%	1.47%	7.10%	1.81%	5.70%	2.48%
15-1111 (all factors)	27.71%	28.54%	16.60%	24.67%	12.48%	20.52%	28.77%	4.52%	32.77%	12.20%

$*$ Refer to Tab. 1 for factor definitions

that the objective function is submodular in the pair of elements. This method does not rely solely on the correlation between variables, so it does not suffer from the same limitations[2]. This method is also stricter in its definition of complementarity due to the specific set of constraints forcing the pairing to be complementary from every possible initial state. Therefore, the number of significant results is limited by the strength of the relationship of the dependent and independent variables.

As an initial starting point, all sources of information support for the implementation of AMT are hypothesized to be complementary to one another. We hypothesize that the plants with a larger and more complex set of information networks to support their implementations of AMT will have the most diverse and up to date set of knowledge to aid in the selection and implementation of the new technologies. Therefore, let $P_j = \sum_{i=0}^{15} \gamma_{ij} I_{ij} + \varepsilon_j$ represent the productivity function for a given industry (or size class) j with 16 possible sources of information support states ranging from 0000 (where none of the support factors are exhibited), to 1111 (where all support factors are exhibited). Similarly, let $\varPi_j = \sum_{i=0}^{15} \gamma_{ij} s_{ij} + \varepsilon_j$ represent the profit function for a given industry (or size class) j. Using these functions, the supermodularity (or submodularity for substitute analysis) constraints were then implemented as a set of restrictions on the coefficients of the variables during the constrained regression analysis.

The initial hypothesis (for complementarity) has as the null hypothesis strict equality and for the alternative that the inequality is negative for all constraints. That is, for analysis of factor 1 (Primary Stakeholders) and factor 2 (R&D) to be complementary,

$$
\begin{aligned}
&H_0:\\
&-\gamma_0(NoFact)+\gamma_4(R\&D)+\gamma_{12}(Prim\&R\&D)=0\\
&-\gamma_1(Corp)+\gamma_5(Corp\&R\&D)+\gamma_9(Corp\&Prim)-\gamma_{13}(CorpPrim\&R\&D)=0\\
&-\gamma_2(Ext)+\gamma_6(Ext\&R\&D)+\gamma_{10}(Ext\&Prim)-\gamma_{12}(ExtPrim\&R\&D)=0\\
&-\gamma_3(Corp\&Ext)+\gamma_7(CorpExt\&R\&D)+\gamma_{11}(CorpExt\&Prim)-\gamma_{15}(All)=0
\end{aligned}
$$

$$
\begin{aligned}
&H_1:\\
&-\gamma_0(NoFact)+\gamma_4(R\&D)+\gamma_8(Prim)-\gamma_{12}(Prim\&R\&D)<0\\
&-\gamma_1(Corp)+\gamma_5(Corp\&R\&D)+\gamma_9(Corp\&Prim)-\gamma_{13}(CorpPrim\&R\&D)<0\\
&-\gamma_2(Ext)+\gamma_6(Ext\&R\&D)+\gamma_{10}(Ext\&Prim)-\gamma_{12}(ExtPrim\&R\&D)<0\\
&-\gamma_3(Corp\&Ext)+\gamma_7(CorpExt\&R\&D)+\gamma_{11}(CorpExt\&Prim)-\gamma_{15}(All)<0
\end{aligned}
$$

The 20 remaining restrictions for the other five technology factor pairings can be expressed similarly by writing the pair-wise restrictions for complementarity from every possible initial support state where the pair of information networks has not already been implemented[16]. For the entire set of sources of implementation support to be complementary for a particular industry or size class, all 24 restrictions must be satisfied. The joint testing of four inequality constraints is required as pair-wise complementarity between any subset of variables implies supermodularity over the subset[21]. These models were repeated for each size class and industry (14 sets in total) as well as for submodularity to test for substitute pairings.

For each size class and industry, a base comparison model was created without any of the supermodularity or submodularity restrictions. A constrained regression model with the complementarity (supermodularity) restrictions as constraints was then calculated for each pair-wise test. Similarly, substitutes were tested using the second hypothesis, which had as the null hypothesis strict equality and as the alternative that the inequality is positive. This resulted in the analysis of 252 regression models for each of the labour productivity and profitability dependent variables. In all cases, a Likelihood Ratio (LR) was calculated[5] as described in[10, 23] to obtain the significance of the results (refer to Tab. 5 and Tab. 6 for size class LR results).

4 Methodology

As previously explained, individual constrained regression models were created for both the profit and labour productivity functions for each pair-wise comparison of factors for every size class and industry in the study. Some of these models were altered due to the lack of plants exhibiting specific states and therefore lack of data for the constraints to model. For this reason, as well as the sample size itself, the values used to determine the significance of likelihood ratio test results vary by both industry and size class. All significance values, as well as the reasoning behind them, can be found in appendix A.

4.1 Size class analysis

First, analyze the constrained regression results by size class with respect to labour productivity. It is believed that availability of strong information support networks should facilitate problem solving by employees to assist with the implementation of the AMT. These information networks should also help to develop effective practices to maximize the efficiency of production using the implemented technologies causing an increase in both labour productivity as well as overall profitability of the plant. There are more significant complementary pairings in small plants than in plants of any other size. These small plants seem to see a greater benefit from a wide variety of information supports (refer to Tab. 5). This may be due to the fact that smaller plants cannot afford to have experts in every area of technology within their organizations and instead rely on generalists internally supported by expert advice from information networks. In particular, primary

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[5] The Likelihood Ratio test statistic is of the form $LR = 2[L(\theta_U - L(\theta_R))]$, where θ_U is the unrestricted Maximum Likelihood estimate of $theta$, and $theta_R$ is the restricted Maximum Likelihood estimate of θ.

stakeholders are complementary with both R&D and external information sources for small plants. Primary stakeholders are found to be substitutes with corporate organizations. This implies that the additional time spent by the labour force to collaborate with corporate organizations does not provide a benefit greater than simply using a single one of these sources. This result is most likely due to the fact that small plants are not part of large companies and do not tend to participate heavily in university research (the main sources of information support for innovations and new technologies offered by Universities).

Table 5. Likelihood ratios by plant size - labour productivity.

	Labour Productivity					
Support Factor Pairs	1-2	1-3	1-4	2-3	2-4	3-4
	Supermodularity Test					
Large Plants	1.169	0.868	0.367	0.234	2.304‡	2.037
Medium Plants	0.130	0.511	72.158*	2.467‡	0.000	0.000
Small Plants	0.013	0.003	71.358*	1.083	1.178	1.005
	Submodularity Test					
Large Plants	0.000	0.000	0.100	0.668	0.067	0.000
Medium Plants	1.532	1.532	0.000	0.000	1.119	2.728†
Small Plants	2.304‡	46.500*	0.000	0.786	0.036	0.480

∗Significant at 0.01,†Significant at 0.05, ‡Significant at 0.10
Refer to Tab. 1 for definition of factor variables.

In medium plants, primary stakeholder and corporate organizations are also substitutes but in this case, external information sources are also found to be substitutes with R&D and complements to corporate organizations. There are limited results for large plants with respect to labour productivity. In this case, only R&D and corporate organizations are found to be substitutes. This is due to the overlap in benefits derived from internal R&D and potential input from university research. Overall, the labour productivity results by size class demonstrate that there are significant differences that exist based on plant size for the optimal set of information support networks to aid in the implementation of AMT and that aggregate analysis will be limited in its usefulness for managers and policy decision makers.

When the constrained regression results by size class with respect to profit demonstrate once again the importance of plant size on complementarities between sources of information support for AMT implementations (refer to Tab. 6). When profit is the objective function there are many significant results for large and medium plants but only one for small plants. This is the complete opposite as when labor productivity is considered, demonstrating that the value derived (and perhaps the original objective for the implementations) from information support networks towards the implementation of AMT is significantly different depending on the size of the plant.

With respect to profit, large plants exhibit two sets of substitute sources of implementation support. The primary stakeholders and the R&D factors are substitutes. This result may be due to the fact that in large plants there are R&D employees that determine what new technology is required in order to make new products and remain competitive so having more people involved will only increase expenses and not provide value added information on the custom solution developed by the R&D department. Once again, the external information sources and the corporate organizations are substitutes.

Large plants also exhibit a number of complementary pairs related to sources of implementation support. The first is that primary stakeholders and corporate organizations are complementary. This result is due to the fact that if all the corporate organizations support the technologies being used, then they will be able to align the products and marketing campaign for the entire company to take advantage of the features inherent in the chosen technology. As well, corporate organizations are complementary with the R&D factor. The complementarity between these two factors derives from eliminating the duplication of research into the technologies between company plants and increasing the sharing of information between the company plants in order to troubleshoot any problems during the implementations. Finally, the R&D factor and external information sources are also complementary. Once again, by using outside sources, the members of the R&D

group will be able to gain greater knowledge about possible technologies implemented in the industry, thus allowing them to find the proper technology for the plant's needs and troubleshoot implementation problems more easily.

Medium plants exhibit a number of significant results with respect to the profit function. As in the analysis related to labour productivity, the R&D factor and the external information sources are substitutes. As in large plants, primary stakeholders and the R&D factor are both complementary with the corporate organizations. There are also a number of other distinct complementary pairs found in the medium plant results. First, the primary stakeholders are complementary with both the R&D factor and external information sources. This is a very intuitive result since when there is support from primary stakeholders any additional support is beneficial to the plant's profit margin. The other pair of complementary sources of implementation support is the external information sources and corporate organizations. This support does not affect the costs of the plant, thus these two combined sources of support will offer a better set of information to the plant for very little cost.

The results for small plants with respect to profit are mostly inconclusive (refer to Tab. 6). There is only one significant result. Primary stakeholders and the R&D factor are complementary. This is similar to the results found with respect to labour productivity, and those of the medium plants with respect to profit.

Table 6. Likelihood ratios by plant size - Profit.

	Profit					
Support Factor Pairs	1-2	1-3	1-4	2-3	2-4	3-4
	Supermodularity Test					
Large Plants	10.529*	0.448	0.506	0.172	0.403	10.987*
Medium Plants	1.195	0.000	1.493	7.765*	0.000	0.896
Small Plants	0.000	0.000	0.000	1.535	1.249	1.665
	Submodularity Test					
Large Plants	0.125	0.053	7.097*	10.071*	9.385*	0.002
Medium Plants	2.688†	3.434†	130.51*	0.747	4.480*	2.389‡
Small Plants	10.563*	1.821	0.989	0.052	0.416	0.572

∗Significant at 0.01, †Significant at 0.05, ‡Significant at 0.10
Refer to Tab. 1 for definition of factor variables

This analysis demonstrates how beneficial it is to have a large number of primary stakeholders involved with the AMT implementation for medium and small plants. The support of primary stakeholders increases the benefits of all other forms of support and is thus critical for small and medium plants to have successful implementations of AMT. The results from the high-level analysis support the results from[22] that the successful implementation of AMT requires strong support from within the organization and a strong champion to lead the implementation within any size plant.

4.2 Industry analysis

A number of exceptions had to be dealt with through model adaptations to the regression constraints due to the sparseness of data for some industries. These exceptions occurred in the machinery industry, which experienced a concentration of plants in only a few states, while the remaining states where very sparsely populated. The distribution of plants in states during the industry analysis had a significant impact on the number of complementary and substitute pairing identified (refer to Tab. 4). There are limited significant results in the analysis by industry but when complementarity is considered, the results with respect to both labor productivity and profit as objectives of supporting AMT implementations are very consistent (refer to Tab. 7). In this analysis, the impact of sample size appears to be significant as only the larger industries exhibit a significant number of conclusive results.

For example, the electronics industry has only one significant result (refer to Tab. 7). The external information sources and the corporate organizations are substitutes with respect to labour productivity. This result may be due to the number of interactions that occur and the differing opinions that may result in this competitive market between the head office of a company and outside market pressures.

The R&D employees and the corporate organizations are found to be complements for the metals industry with respect to both the labour productivity and profit models. The R&D factor is also a complement for the external information sources with respect to profit. These results demonstrate that in the metals industry, the R&D group appears to be the internal champion for the use of AMT and that any support from outside the plant that they can obtain increases the effectiveness of the implementation. A constraint to this conclusion is that the external information sources and the corporate organizations are substitutes with respect to profit. This result implies that a plant should only use one source of external support, as using both simultaneously may lead to conflict and confusion and the additional investment does not produce enough results to match the marginal cost.

The textiles industry has the opposite result to that of the plastics industry, as the primary stakeholders are complementary to the external information sources with respect to labour productivity, and complementary to corporate organizations with respect to both models. As in the machinery industry, the primary stakeholders in the textiles industry are better able to champion change when they have support from outside the plant. This result demonstrates the importance of primary stakeholders in the textiles industry.

Primary stakeholders are complementary with external sources of support but substitutes with corporate organizations for plants in the furniture industry. The results are identical for both objectives demonstrating a clear policy statement for managers in this industry. The substitute nature of corporate organizations may be due to the large number of smaller, custom furniture, plants in this industry.

Table 7. Likelihood ratios by plant size - Profit.

	Supermodularity		Submodularity	
	Labor Productivity	Profit	Labor Productivity	Profit
Chemical				
Electronic	3-4†			
Furniture & Other	1-4*	1-4‡	1-3†	1-3‡
Machinery	2-4†	2-3*, 2-4*		1-2†, 1-3*, 1-4†
Metal			2-4*	2-3*, 2-4*
Non-Metal				
Plastics		1-4*, 3-4*		
Textiles			1-3*, 1-4†	1-4*
Vehicles	1-2‡, 2-3*, 2-4†	1-4*		
Wood	1-2‡, 1-3†, 1-4†, 2-3*	2-3*	1-2*, 1-3†, 3-4*	1-2*, 1-3‡, 3-4†

∗Significant at 0.01, †Significant at 0.05, ‡ Significant at 0.10

Refer to Tab. 1 for definition of factor variables. Likelihood ratio results available from the author upon request

In the machinery industry, primary stakeholders complement all other forms of information network supports in the analysis with respect to profit. R&D sources of information support are substitutes with both external sources and corporate organizational sources of support. These results once again provide important feedback to managers on the set of practices they need to have in place to support successful AMT implementations. The results indicate that in all cases, primary stakeholders are important in the machinery industry and represent the primary source of information for AMT implementations. They also demonstrate that investing heavily in information networks around R&D may be more beneficial than investing in external and corporate organization information networks. Further analysis is required to determine if the cost of the substitute pairing is greater than the complementary benefits which can be derived from the pairing of the factors. This type of analysis will be demonstrated later when we consider the example solution lattices where the size and impact of the complementarity or substitute effect can be more easily visualized.

The profile of the vehicle industry results is unique as there are only substitute pairings found. In the vehicles industry, R&D sources of information support are substitutes for all other forms of support infrastructures with respect to labor productivity. These results demonstrate the important role that R&D has on the successful implementation of AMT in the vehicles industry. The results also highlight the impact that the unique manufacturing environment that has developed between suppliers and manufacturers within the automotive sector has had the importance and nature of information supports within the industry.

In the wood industry, corporate organizations are substitutes with primary stakeholders in the labor productivity model while at the same time they are complements to external sources of implementation support. External sources are also substitutes with R&D. This is the only industry where a pair-wise comparison rejects both the supermodularity and submodularity conditions. This occurs between primary stakeholder sources and both R&D and external sources of information support with respect to labor productivity. This implies that further analysis is required and that there may be a confounding industry specific effect that is not included in the analysis, such as the specific makeup of elements in the primary stakeholders factor that significantly influences the constraints. With respect to profit, both of these pairing, primary stakeholders and R&D or primary stakeholders and external sources, are complements.

5 Discussion

The analysis by size class supports previous studies[12] that the use of AMT is significantly different based on plant size. The implications of the size class results is that primary stakeholders are an extremely important source of information support but that through the conduct of R&D some of these information networks may be substituted. The results for the industry analysis also support previous work[6, 15] as it is clear that industry plays a significant role in determining the types of information support networks that contribute to successful implementations of AMT.

In the industry analysis, the results remain relatively consistent if either model labor productivity or profitability is analyzed. The results are very different when plants are classified only by size class. In the size class analysis, the nature of the objective function plays a decisive role in determining the optimal set of policies to support the implementation of AMT. This demonstrates the need for all future research to consider both labour productivity and profitability measures when managers are developing their organizational and information structures to support AMT implementations.

In most cases, considering only the constrained regression results will lead to a number of possible state solutions as there are a number of inconclusive results. Determining the optimal state based solely on this information is also not possible as the impact of each substitute or complementary pairing is unknown and it would be unclear to managers if the benefit of including a factor, as it was complementary with two others, would outweigh a substitute effect between the factor and a third component. This is primary situation when the consideration of the solution lattice can aid in demonstrating which pairings are optimal and which results have the most significant impact. The use of the lattice solutions can also aid in demonstrating the best path a plant can take in moving from its current state to the optimal state.

5.1 Size class solution lattice example

To demonstrate the application of the results for plant managers by size class, an example solution lattice for medium plants has been developed. The nodes in the lattice represent each of the possible information support states in which a plant might currently occupy (refer to Tab. 1 for factor definitions). The vertical access represents the average profit margin (manufacturing value added per shipment dollar) of firms in the particular state (a similar lattice could be developed to represent the results of the labour productivity analysis). The scatter-plot diagrams include an example optimal path that a manager would take to move from a poor performing state to the optimal state in only single step movements (e.g. only the investment in only one factor at a time is altered in each step). It is possible for a manager to select to move faster across the lattice if there are no other organizational constraints such as cultural or capital needs representing obstacles to progression.

A manager should always attempt to move as quickly as possible through the lattice as there are significant advantages to be gained in the optimal state (refer to Fig. 2).

In the diagram representing medium plants, there are instances where the complementary or substitute pairing does not appear to be a complement or substitute from the zero state (no factors exhibited) but is from many of the other possible starting states. This is due to the statistical significance level used in the regression analysis and the size of the difference between the profit measures in the various states. In the constrained regression analysis, it is possible for the constraints to be met because one of the state coefficients is very small or very large so that the factors may not appear to be strictly complementary or strictly substitutes in the lattice plots.

The complementary pairs of the primary stakeholders and the external information sources (26.30%), external information sources and corporate organizations (28.82%), and R&D and corporate organizations (37.78%) all have better average profit margins when compared to the initial zero state (24.06%). The substitute pairing of the R&D group and external information sources (factors 2 and 3) is marginally supported as even though the state consisting of only these two factors (state 0110) performs slightly better that state zero; none of the top tier states (those with an average profit margin greater than 30%) contains the two factors. The lower tier states (those with profit margins less than 20%) represent 8.02% of medium plants, almost double the 4.25% represented by top tier states. In this case, plants in the optimal state of research and development and corporate organizations (state 0101) perform much better (almost three times better) than the worst state (state 0111).

The cost and time involved in moving from one of the lower tier states to the optimal state may be quite large, so the plot identifies the path that should be taken to have the greatest impact with the smallest amount of change to current practices and structure. Managers are be able to use the plot to identify better performing states and then determine the optimal state they can achieve given their budgetary and organizational constraints. The optimal state may also not be possible for many firms due to other internal or cultural barriers; in which case they can identify the best possible state that they can attain. The use of lattice plots will assist plant managers in determining the specific set of policies that they should create in their organization given a restricted budget by prioritizing the changes that need to be made in order to exhibit the optimal state or at least one of the top tier states to support the implementation of AMT.

5.2 Industry solution lattice example

Similar to the example lattice plot for the size class analysis, one of the larger industries (vehicles) was selected as an example case for the industry analysis solution lattices. The nodes once again represent the possible states of uses of information networks to support the implementation of AMT. In this case, there is over a 40% difference in the profit margin of the worst performing state to that of the optimal performing state (refer to Fig. 3). These results demonstrate the importance of understanding complementarities between information networks and finding the proper fit to support the implementation of AMT.

The analysis of the lattice of sources of implementation support for the vehicles industry confirms the substitute pairing of support from primary stakeholders and corporate organizations. The upper tier of states, those with average profit margins above 0.3 (states 1011, 0100, 0101, and 0111), represents 21.93% of vehicle plants (refer to Tab. 4). In particular, the two states with average profit margins greater than 0.4 (states 0100 and 0101) represent 7.47% of the vehicle industry. These two states both contain support from the R&D information network indicating the importance of new designs and innovations to the vehicles industry. The lower tier of states, those with average profit margins less than 0.12 (states 1000, 1001, and 0010), represents over 38.62% of vehicle plants. These results demonstrate that many have the opportunity to quick move to a better performing state that will provide them with immediate returns through better integration and implementation of their AMT.

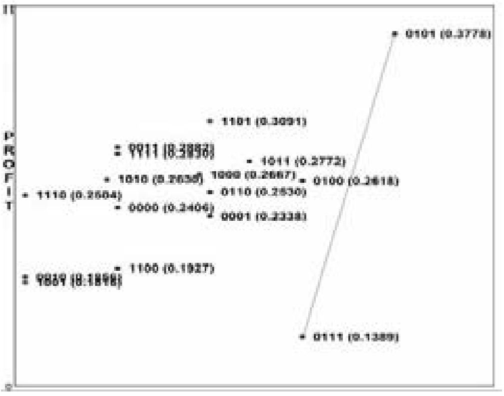

Fig. 2. Plot of example solution lattice for Medium Plants

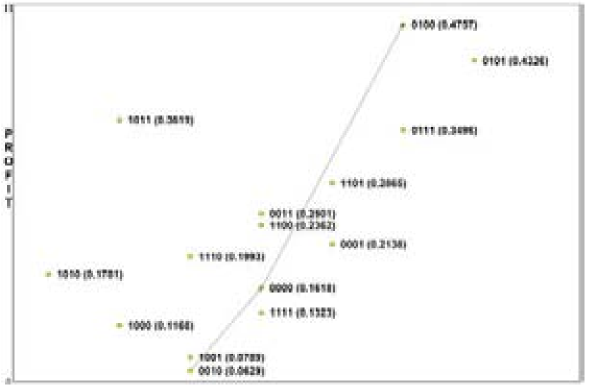

Fig. 3. Plot of lattice of sources of implementation support - Vehicles Industry

6 Conclusion and future research

The need to create the appropriate set of information support networks to aid in the implementation of AMT is supported throughout this analysis. The differences based on size class and industry is significant and there is no factor pairing which is complementary for all the majority of parings. These differences support the need for future research at both the size class and industry level to identify the specific information support networks that result in the greatest benefit in aiding in the implementation of AMT. It is clear, that analysis on amalgamated data, although the sample size would be significantly improved, would result in confounded results with little application benefit at the organization or plant level.

The example solution lattices demonstrate the practical application of the constrained regression results for plant managers. The diagrams aid managers to visually identify the impact of specific complementary and substitute pairings on either labour productivity or profit margins. The optimal traversing of the lattice for a specific plant may be constrained by availability of capital or cultural concerns. Although it may not be feasible for a plant to move to the optimal state, the lattice plot does demonstrate opportunities to improve that can fit into any set of organizational constraints.

There are some limitations to the research that should be noted. An initial limitation is that the sample is not evenly distributed in all possible states. When there are no representatives in a state, the model was altered, it is unclear if the lack of plants in the state is due to that particular states poor performance or simply a nature evolution where no plants attempted to move into that particular structure. If the reason is poor performance, then the alterations completed to the model may not represent the importance of the negative pairings.

A second limitation is that due to the sparseness of the data in the various information support states, the number of factors had to be restricted to four. The limited number of factors results in only high-level conclusions being able to be drawn as the clusters of information support networks in each factor might differ based on industry, plant size, or even individual plants. It is left for future research to determine if the differences in the clusters is responsible for the limited significant results or if there are some external management practices or organization structure decisions that are confounding the results.

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Appendix A

Table 8. Significance values for likelihood ratios of sources of implementation support

	$\alpha = 0.01$	$\alpha = 0.05$	$\alpha = 0.1$
1	3.78	2.61	2.08
2	4.92	3.12	2.38
3	4.07	2.73	2.16
4	3.99	2.70	2.14
5	4.61	3.00	2.30

(1) These significance values are for all tests by size class and all industries except the machinery and non-metals industries, and tests of the second and third, first and second, and first and third factors of the textiles industry.

(2) These values are for all tests involving the fourth factor in the machinery industry.