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Prioritization Methodology for Resin Infusion Research

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16. Abstract

This work is the first academic application describing the prioritization methodology for resin infusion research using the New Product Blueprinting (NPB) process developed by the AIM Institute. It is intended to be read in conjunction with DOT/FAA/TC-23/2, *Resin Infusion – State of the Industry* to fully understand the benefits, shortcomings, and necessity of research of resin infused aerospace parts. This process identifies, qualifies, and quantifies problem statements found in the aerospace industry that are preventing adoption of resin infusion. Approximately thirty interviews were conducted up and down the value stream to identify the top ten problem statements for resin infusion. Interviewees included original equipment manufacturers (OEMs), raw material suppliers, tier 1 suppliers, new and experienced users, and providers of machine solutions. Subsequently, approximately thirty additional interviews were conducted to quantify the satisfaction and importance of each of these problem statements.

Using the NPB process eliminates bias in the selection of research topics and allows for a holistic approach to industry guided research programs. The data collected herein will be used to identify research topics, through the examination of industry satisfaction gaps that require devoted research to achieve satisfaction within the aerospace industry.

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Acronyms

Acronym	**Definition**
ACI	Advanced Composites Institute
CMC	Ceramic matrix composite
CMH-17	Composite materials handbook
FVF	Fiber volume fraction
ISG	Industry satisfaction gaps
KPI	Key performance indicators
NCAMP	National Center for Advanced Materials Performance
NPB	New Product Blueprinting
OEM	Original equipment manufacturer
R&D	Research and development
SRI	Stitched resin infused
VOC	Voice-of-the-customer

Executive summary

The purpose of utilizing a New Product Blueprinting (NPB) process developed by the AIM Institute to prioritize research goals is to remove bias by identifying and quantifying market satisfaction gaps through a multi-staged interview process. These gaps are determined from the collected problem statements, identified in the first stage of the process, and highlight areas that should receive further research and development (R&D). For the purpose of this report, the team decided the AIM Institute “market satisfaction gaps” are better represented as industry satisfaction gaps (ISG) for the purpose of research planning.

The entire value stream for commercial aerospace was interviewed: original equipment manufacturers (OEMs), tier 1 suppliers, raw material suppliers, new and experienced users, and machine solution providers. The top 10 problem statements identified were manufacturing consistency, a trained workforce, automation of the preforming process, a public material database, accurate simulation, consistent fiber volume fraction (FVF), a high toughness, microcracking, fast cure time, and a long pot life. Please refer to DOT/FAA/TC-23/2, *Resin Infusion – State of the Industry* for further understanding about why these problems are of particular interest during the resin infusion process.

The output of the NPB process are quantifiable metrics, most notably importance vs. satisfaction data. Data collected during the second phase of the interviews highlight the most important and least satisfied problem statements and are used to produce an importance vs. satisfaction matrix. Different value stream positions (i.e., OEM and raw material suppliers) had some agreement in the importance vs. satisfaction plots for their opinions of industry satisfaction. However, there were numerous problem statements that had unique locations in the plots dependent on the interviewee’s different value stream segments. This unveils the power of this process: interviewing companies up and down the value stream (along with various stakeholders), a complete dataset can be collected, while covering and capturing a more accurate picture of the industry’s perspective.

The largest difference between the NPB process and traditional industry studies is the ability to determine quantitative metrics to fully satisfy the industry. The preference interviews probe what targets and what methods of measurement are required to fully satisfy the interviewees for each individual problem statement. Therefore, this research can uncover problem statements preventing adoption of resin infusion for aerospace, but also provide insight on how to remediate these problem statements.

Overall, this is the first application of the NPB process in academia, and the collected data in this report will help direct future projects for the Mississippi State University Advanced Composites Institute (ACI). This ensures the research is relevant to the industry stakeholders, along with the funding agencies.

1 Introduction

Often businesses lean on their expertise and experience to focus on specific novel products or allocation of research and development (R&D) resources. Alternatively, industry reports are a methodology to ascertain industry directions and needs; while very useful, these industry reports can only offer directionality for a novel product or research topic; they do not offer quantifiable data for industry satisfaction and industry gaps. In a worst-case scenario, new products can be brought to industry that do not fulfill the needs of the customers. To mitigate the risk of irrelevant products, (i.e., physical or research), a Voice-of-the-Customer (VOC) process can be used to identify areas in the industry space that are important to the domain (i.e., business-to-business (B2B) or business-to-customer (B2C)) and to elucidate their satisfaction. Using a VOC analysis allows for a quantitative metric to be assigned to the identified industry gaps, allowing for clear and concise research focal points and elimination of biases.

While often utilized in industrial settings, a VOC analysis has largely been forgotten by academia. In this report a VOC procedure with strict milestones and goals has been followed to identify, quantify, and prioritize industry satisfaction gaps (ISG) for aerospace applications of resin infusion. These ISG are a source to highlight areas of high importance and low satisfaction and will allow the Mississippi State University Advanced Composites Institute (ACI) to direct future research plans to help meet and address these identified ISG. Not only does the VOC analysis identify ISG, it uses a process called New Product Blueprinting (NPB) developed by the AIM Institute, and also determines quantitative metrics to meet the ISG identified during the industry interviews. The metrics associated with satisfying the ISG allow for explicit goals to fully satisfy the industry. Thus, the NPB process will aid the ACI in deciphering what research goals to pursue in the future.

1.1 Discovery

An overview of the NPB process is found in Figure 1. The process begins with the discovery phase where many companies all along the value stream were interviewed: raw material suppliers, machine solutions providers, simulation providers, tier 1 suppliers, and original equipment manufacturers (OEMs). For this specific scope, interviewees were asked, “What do you think the problems are with resin infusion that prevents higher adoption for commercial aerospace?” and their answers were recorded in a brainstorming style on sticky notes (Figure 2). The data is recorded verbatim from the interviewees to ensure exclusion of interpretation by the interviewer. Additionally, only problems were discussed, no solutions. All ideas were collected on sticky notes and then summarized by a short phrase called the *problem statement*.

The problem statements provided ease of understanding and ensured accurate collection of the ideas. A typical interview provided 10-15 different problem statements from which the top 3-5 problem statements (denoted by *TP*, top picks in a red circle in Figure 2) were chosen. This process was followed for every interview, regardless of the value chain position. As more interviews were completed, the top picks identified during each interview began to be duplicated. The purpose of the discovery phase was to identify the top picks and a good indication that all pertinent top picks had been discovered was when new top picks were no longer being identified. Thirty interviews were conducted for this research.

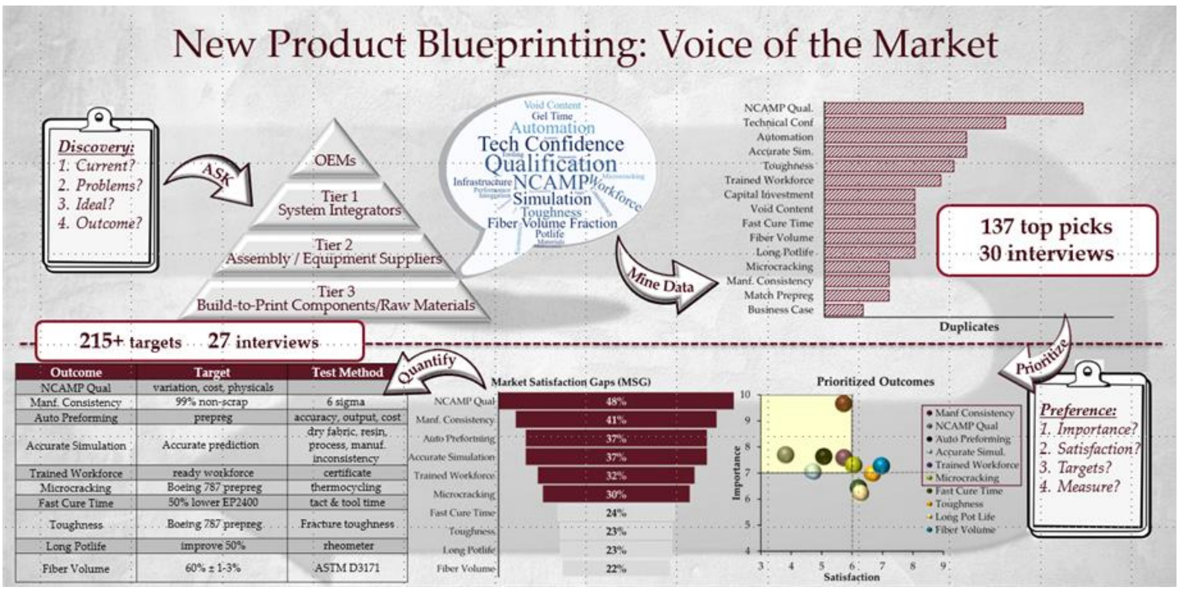


Figure 1. Overview of New Product Blueprinting process

Figure 2. Discovery interview interface

Upon completion of the discovery interviews, the totality of the top picks was categorized into smaller groupings of similar top picks (Figure 3). During our discovery interview process, 137 total top picks were identified and then separated into 29 overall categories.

Inevitably, all the top picks collected will not be identical in verbiage, but the interviewer uses their experience to accurately categorize differently worded top picks. The number of duplicated top picks contained within each category is found in the top right of each sticky note in Figure 3. The most duplicated categories from the discovery interviews typically determine the top 10 problem statements investigated during the preference interviews, but the number of duplicates does not indicate the importance or satisfaction of these ideas – the top 10 problem statements (or more likely less than 10) would be a typical output of an industry report. Table 1 shows the top 10 problem statements uncovered during the discovery interviews.

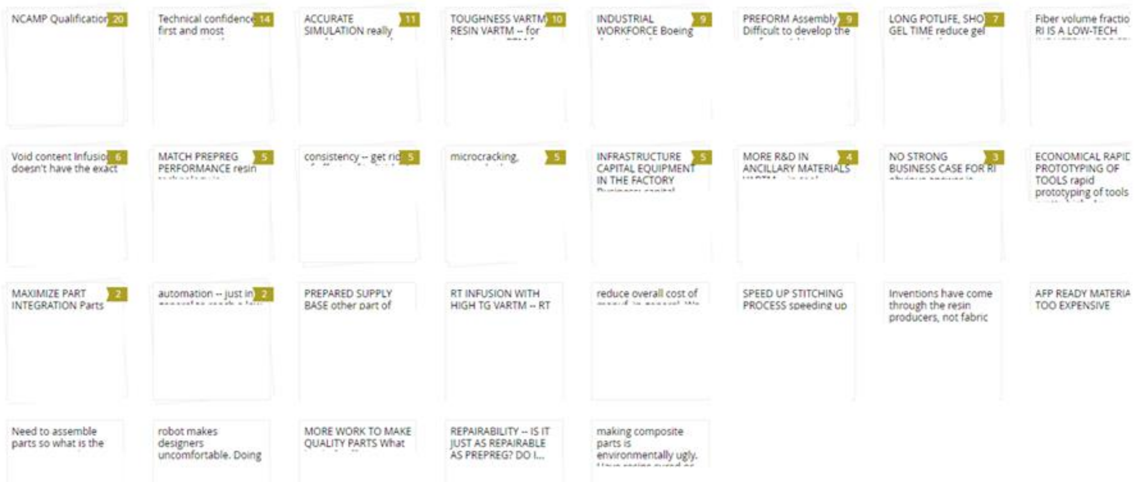


Figure 3. Preparation of top picks collected during discovery interviews

Table 1. Problem statements identified during discovery

Provide publicly available material qualification database	Provide accurate simulation	Have a high toughness	Provide a well-trained workforce	Automate preforming
Maximize pot life	Have a consistent fiber volume fraction	Minimize cure time	Provide manufacturing consistency	Minimize microcracking

1.2 Preference

The interface during preference interviews is found in Figure 4 and shows how the importance and satisfaction data were collected during the first stage of the preference interviews. In the first stage, interviewees were asked about the importance and satisfaction for each of the top 10 problem statements identified and all comments were collected. The second stage of the preference interview determines the target to fully satisfy each problem statement and what relevant test methods should be applied (Figure 5). Twenty-seven interviews were conducted during the preference stage. As previously stated, the NPB process uniquely allows for quantification of these problem statements through the importance vs. satisfaction data and the target and method data.

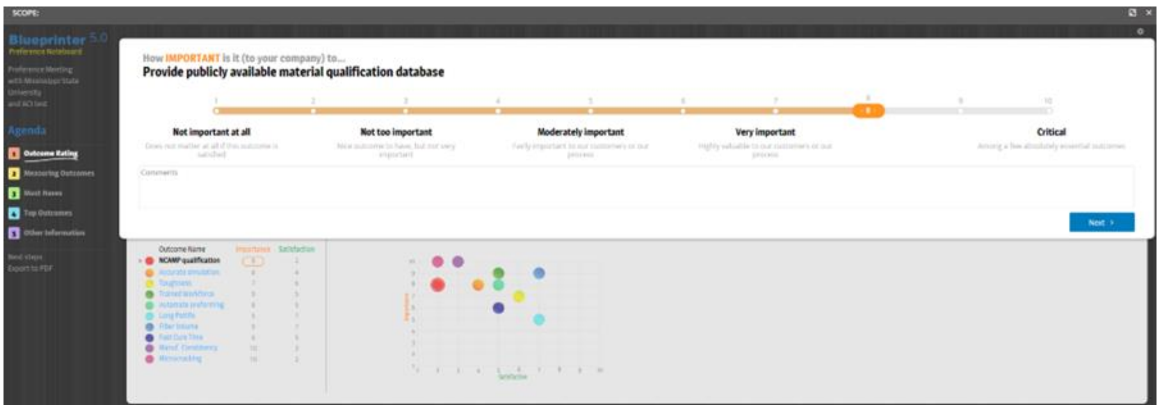


Figure 4. Interface during preference interviews

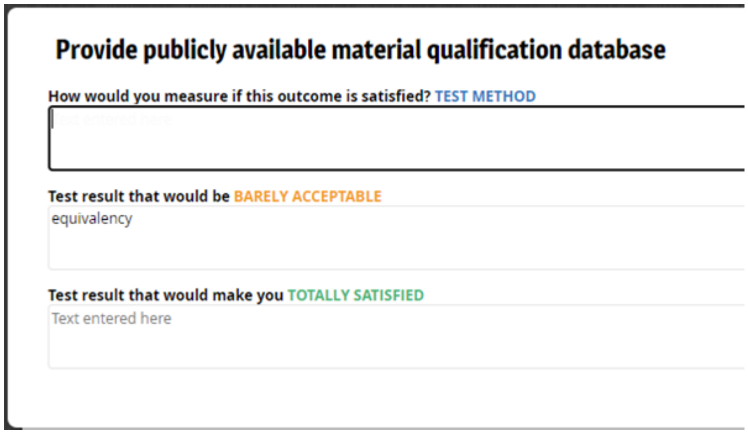


Figure 5. Collection of target and method data during preference interviews

2 Results and discussion

The first output from the preference interview stage is the importance vs. satisfaction plot. This plot highlights what problem statements should be first addressed by focusing on the most important and least satisfied problem statements found in the top left quadrant of the plot. From this data, industry satisfaction gaps can be calculated using 1, where ISG > 30% are considered significant.

$$Market\ Satisfaction\ Gap = Importance\ (10 - Satisfaction) \quad (1)$$

The definitions for the rating scale for the importance and satisfaction are found in Table 2.

Table 2. Description for importance and satisfaction ratings

Rating	**Importance**	**Satisfaction**
1	Not important at all	Totally unsatisfied
3	Not too important	Unsatisfied
5	Moderately important	Barely acceptable
7	Very important	Good
10	Critical	Totally satisfied

2.1 Importance vs. satisfaction data

2.1.1 Entire industry

The importance vs. satisfaction plot and ISG for the entire industry data collected is found in Figure 6. No single problem statement has a satisfaction above 7, a rating of "good", suggesting the correct problem statements have been captured; additionally, almost all the problem statements were rated at an importance of 7, a rating of "very important", or higher.

A publicly available material qualification database is the least satisfied problem statement, also reflected in it being the largest ISG. Typically, interviewees suggested the National Center for Advanced Materials Performance (NCAMP) data is at a satisfaction of 7 when entries exist in the database but provided a low satisfaction level overall because there was no resin infused materials in the current database. There is a significant cost and time associated with building up a wide public database with as many database entries as possible. The target for a public database is found below in section 2.2 Targets and Methods.

Manufacturing consistency was identified as being of critical importance. This highlights the top right quadrant of the plot: any problem statements to be first addressed (i.e., NCAMP qualification and accurate simulation) can only be fully satisfied when items in the top right quadrant of the importance vs. satisfaction plot persist in the top right quadrant. Other problem statements, like consistent fiber volume fraction (FVF), toughness, and microcracking fall within the top right quadrant as well. As the FVF is not strictly measured prior to infusion like in prepregged materials, there is some hesitancy with ensuring the correct FVF along the entire part, especially in deep draws and radii. Despite the ability to directly control the amount of resin injected into the part, the ability to tightly control the location of the resin is more difficult for resin infusion. Additionally, the viscosity of the resin is highly dependent upon temperature and will directly affect the resin infusion process, along with the fiber type, layup, bulk, and nesting.

Toughness and microcracking were also in the top right quadrant as the current toughness of the resin systems for aerospace resin infusion was deemed satisfactory; however, not all parts require a high toughness. Therefore, the toughness metric was not applicable for every single infused part.

Older toughening methodologies would add rubbery particles to the resin, but this could perform poorly during an infusion as the particles could be filtered by the fabric reinforcement. Newer systems have been able to address this issue with toughening veils that are designed for resin infusion processes. Commercial aviation is risk-adverse industry, and any new technology needs to clearly demonstrate safety and performance prior to higher adoption rates.

Directly related to toughness, microcracking also is also rated satisfied as typical resin infusion processes do not have limitations due to microcracking; however, microcracking was identified as a major concern for stitched resin infused (SRI) parts, something that could not be fully investigated during our interviews as few have experience with SRI. The interviewees identified minor issues with microcracking of non-stitched infused parts immediately after production.

Fast cure and long pot life were initially identified as a combined problem statement during the discovery interviews, where interviewees desired an infinite pot life and an immediate cure. These items were separated during the preference interviews to probe if either parameter was more important and/or satisfied; in this case, it appears both fast cure and long pot life were well satisfied and the least important of the problem statements. This helps to highlight the importance of the entire NPB process as the discovery interviews showed the cure time and pot life would be viewed as equally important topics to pursue. This is not to suggest that fast cure time or long pot life should not be investigated, but they should not be addressed initially.

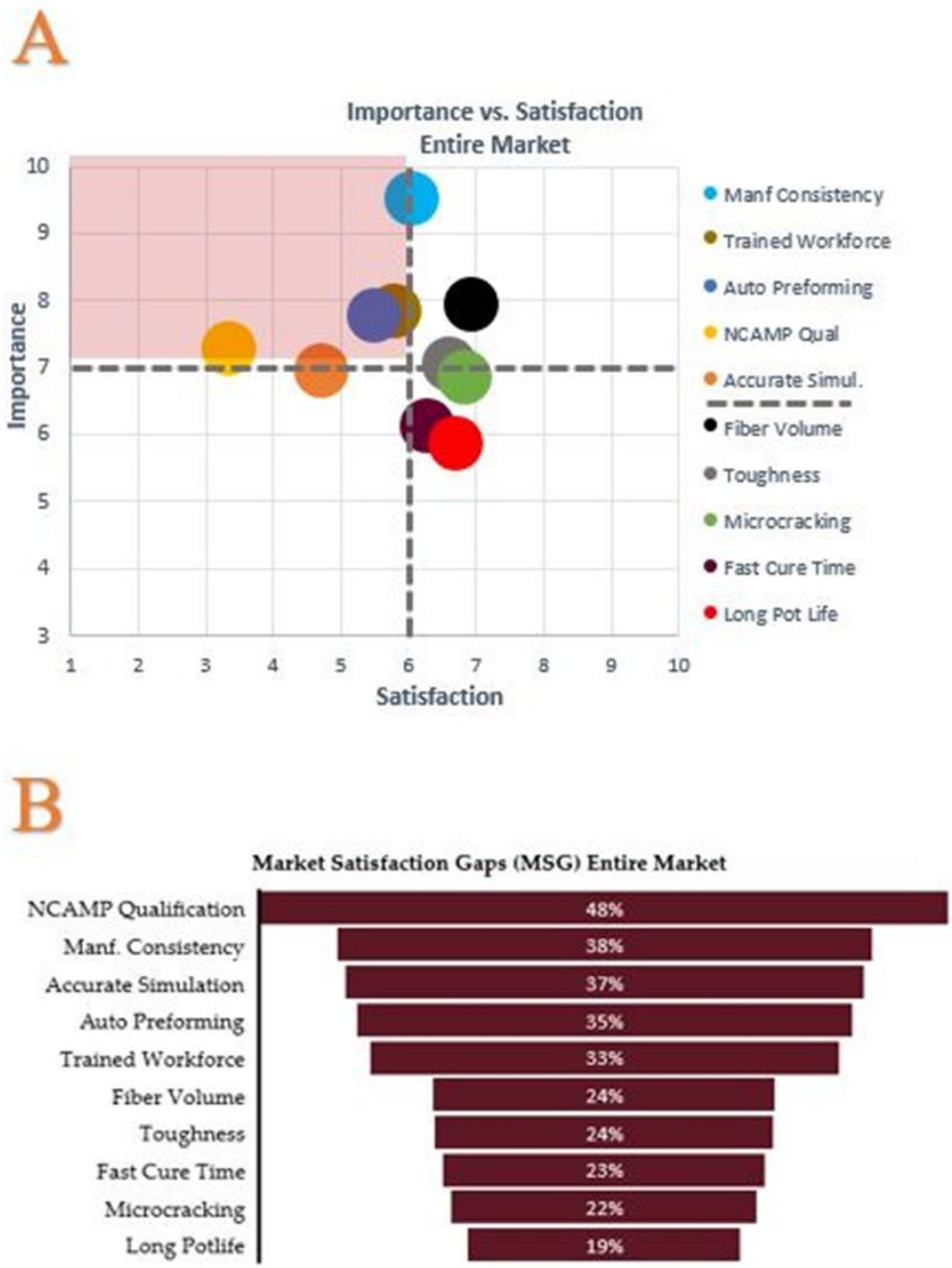


Figure 6. Data for entire aerospace resin infusion industry

A) Importance vs. satisfaction plot for aerospace resin infusion entire industry

B) Industry satisfaction gaps for aerospace resin infusion entire industry

2.1.2 Original equipment manufacturer (OEM)

Five of the 10 problem statements found during discovery were considered *critical* to the OEMs interviewed as shown in Figure 7.; 7 of the 10 were considered at least as very important. This fact again suggests that the discovery interviews succeeded in capturing the correct problem statements with importance to the industry. Only 4 of the 7 of these very important problem statements have an industry satisfaction gap > 30%, and three of these (accurate simulation, automation of the preform, and fast cure time) have the same ultimate end goal of increased manufacturing rates.

The OEMs were very interested in moving the design process into a digital format to help improve quality and lower development time; it was stressed that prepreg composites also struggle with this challenge. Prepreg has had more developmental time than resin infusion but there are still significant industry satisfaction gaps -- the struggle for simulation for infusion does not uniquely disqualify it. Additionally, simulation covers the gamut from the infusion itself all the way to the factory floor and production; virtual production of the part helps to mitigate manufacturing complications.

The OEMs were the only group interested in microcracking as it is difficult to simulate and thus difficult to analyze and certify. One example provided as a successful campaign to understand and utilize microcracking was for ceramic matrix composites (CMC) where microcracking adds a pseudoplasticity to improve damage tolerance. Work planned within this project will develop a non-linear damage model for stitched composites to aid design and understand failure mechanisms.

A fast cure time was also very important to the OEMS, but this was interpreted slightly differently than the intended direction of a rapid resin cure. The resin cure is only a fraction of the total time to produce a part and the OEM wants to reduce the on-tool time. This dovetails with automation of the preforming process as it can help to increase quality, lower costs, and increase rates. The goal is to produce aerospace parts at automotive rates; preform automation, better simulation, and a high manufacturing consistency all contribute to reducing the overall manufacturing time.

A

B

Figure 7. Data for OEMs of aerospace resin infusion industry

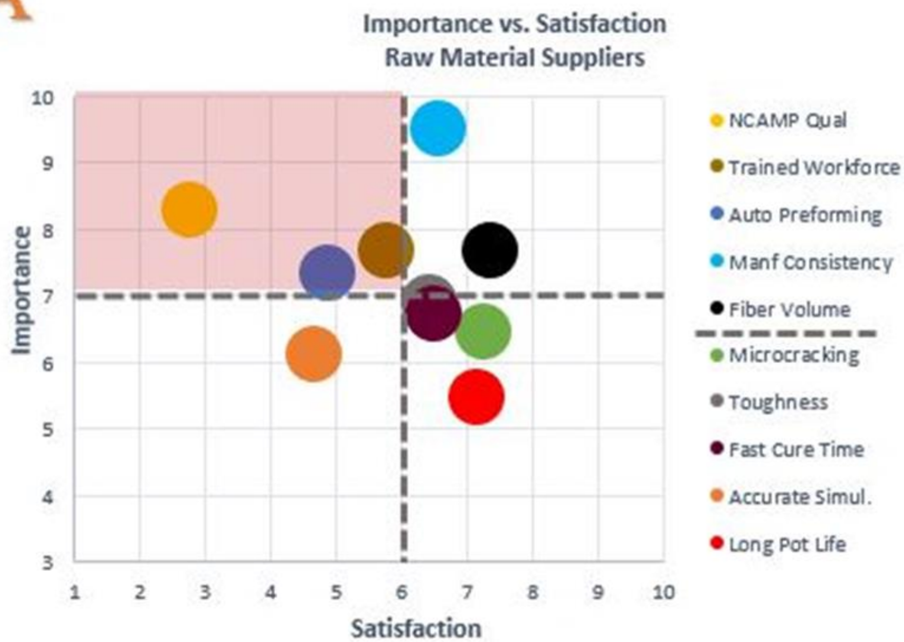
A) Importance vs. satisfaction plot for OEM for aerospace resin infusion industry

B) Industry satisfaction gaps for OEM for aerospace resin infusion industry

2.1.3 Raw material supplier

The importance vs. satisfaction plot and ISG plot are found in Figure 8 for raw material suppliers. A public material qualification database was rated as very important but with the least satisfaction. The data appears accurate as having their materials in a public database is a highly valuable business proposition for suppliers. Also, there is a higher focus on automated preforming, which makes logical sense as a raw material supplier needs to sell materials that are amenable for automation. In general, the raw material suppliers' responses show good coherency with the entire industry. Accurate simulation is less important to raw material suppliers, although they may be able to provide a crucial role for the input variables for simulation. Providing partial simulation input parameters into technical data sheets and/or a public database will dramatically aid simulation adoption.

A



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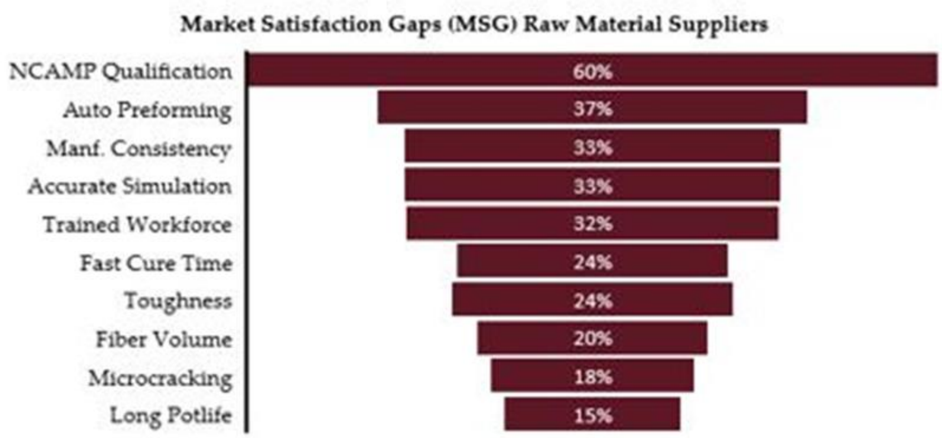


Figure 8. Data for raw material suppliers of aerospace resin infusion industry

A) Importance vs. satisfaction plot for raw material suppliers for aerospace resin infusion industry

B) Industry satisfaction gaps for raw material suppliers for aerospace resin infusion industry

2.1.4 Tier 1 supplier

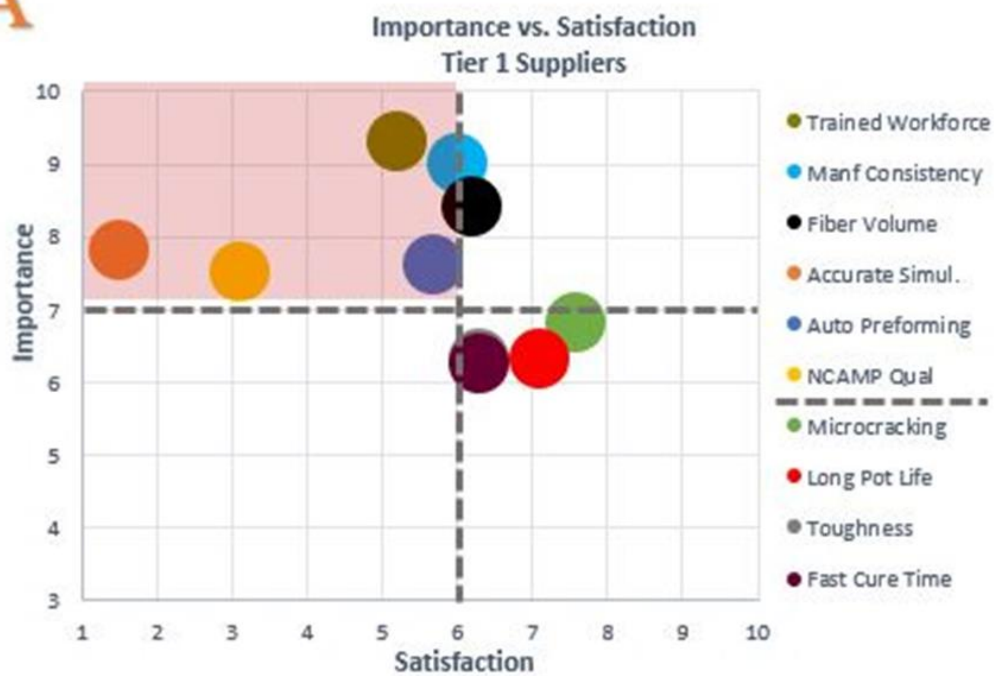
The tier 1 supplier data shows their biggest interests are tied to the manufacturing process and challenges as shown in Figure 9. The six problem statements found in the top left quadrant indicate the overall process for resin infusion may have much room for improvement. The largest ISG is for accurate simulation, consistent with the entire industry, but the satisfaction is much lower for the tier 1 suppliers. Accurate simulation is more aligned with the tier 1 suppliers business model of producing parts for OEMs as performing simulation to lower the development costs and increase speed is of great priority. More research needs to be conducted to investigate if the identified industry satisfaction gap is due to a limitation to the current software capabilities or due to further growth opportunities for tier 1 suppliers. This problem statement was intentionally left broad to cover all facets of simulation as all the following topics were identified during the discovery interviews: resin flow, cure, internal stresses, dry fabric drapability, and the manufacturing process. It is suggested the NPB process should be used to produce very specific targets for simulation.

The amount of material data in a public material qualification database for resin infused parts is significantly less than the amount of data for prepregs. This significantly impacts the satisfaction for a public material database and shows the tier 1 suppliers may choose resin infusion as a competitive technology if the database was populated with infused materials. Our interviews showed the data in the NCAMP database is typically satisfactory but has areas for improvement.

The bottom right of the importance vs. satisfaction plot shows raw materials development is not as important to the tier 1 suppliers. This indicates they can produce acceptable parts with the current resin chemistry, cure time, and pot life; these problem statements are still important, however, as they were identified as a problem during the discovery interviews.

The tier 1 suppliers were identified as crucial for these interviews as they are producing parts for OEMs and have produced infused parts, working through all the problem statements identified in this research, but also fully understand key performance indicators (KPIs) to mature technology. It was indicated resin infusion has many advantages over prepreg materials; please see "DOT/FAA/TC-23/2, *Resin Infusion – State of the Industry*" for more specific information about the business and technology advantages of resin infusion. We were directly told resin infusion, while a novel technology, will be/is chosen due to a favorable return on investment and a strong business case; therefore, we expect the importance vs. satisfaction plots will change over time with higher adoption of this technology due to favorable business cases causing higher adoption.

A



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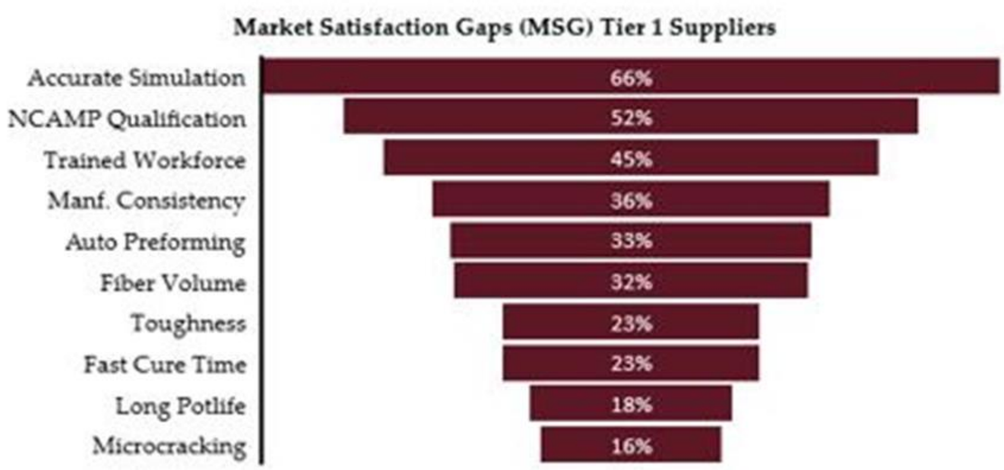

Figure 9. Data for tier 1 suppliers of aerospace resin infusion industry

A) Importance vs. satisfaction plot for tier 1 suppliers for aerospace resin infusion industry

B) Industry satisfaction gaps for tier 1 suppliers for aerospace resin infusion industry

2.1.5 New users and experienced users

The data separated by user experience is found in Figure 10 and Figure 11. The experience level assigned to the interviewees was determined by the interviewer, but often was self-identified by the respondents. The experienced users data have a clear distinction between the top 5 and bottom 5 problem statements (Figure 10A), while new users (Figure 11A) only identify manufacturing consistency and fiber volume as problem statements found in the top left quadrant. The five problem statements found in the top left quadrant in the experienced users data are all research topics by themselves and will undoubtedly spur further research into these areas. Furthermore, it is expected that future industrial collaborations will develop to help address these issues as many relationships have been established during the interview process.

Additionally, the data for the ISG for the new users and experienced users show large discrepancies; this may suggest there is a perception issue for resin infusion for new users. While not unexpected, it does suggest that further education around the capabilities for resin infusion would help future decision-makers make more accurate decisions with a better dataset. A great start would be populating the NCAMP database with many fabrics, resins, and layups for resin infused parts to allow design engineers the ability to peek behind the curtain and better understand the capabilities for infused parts.

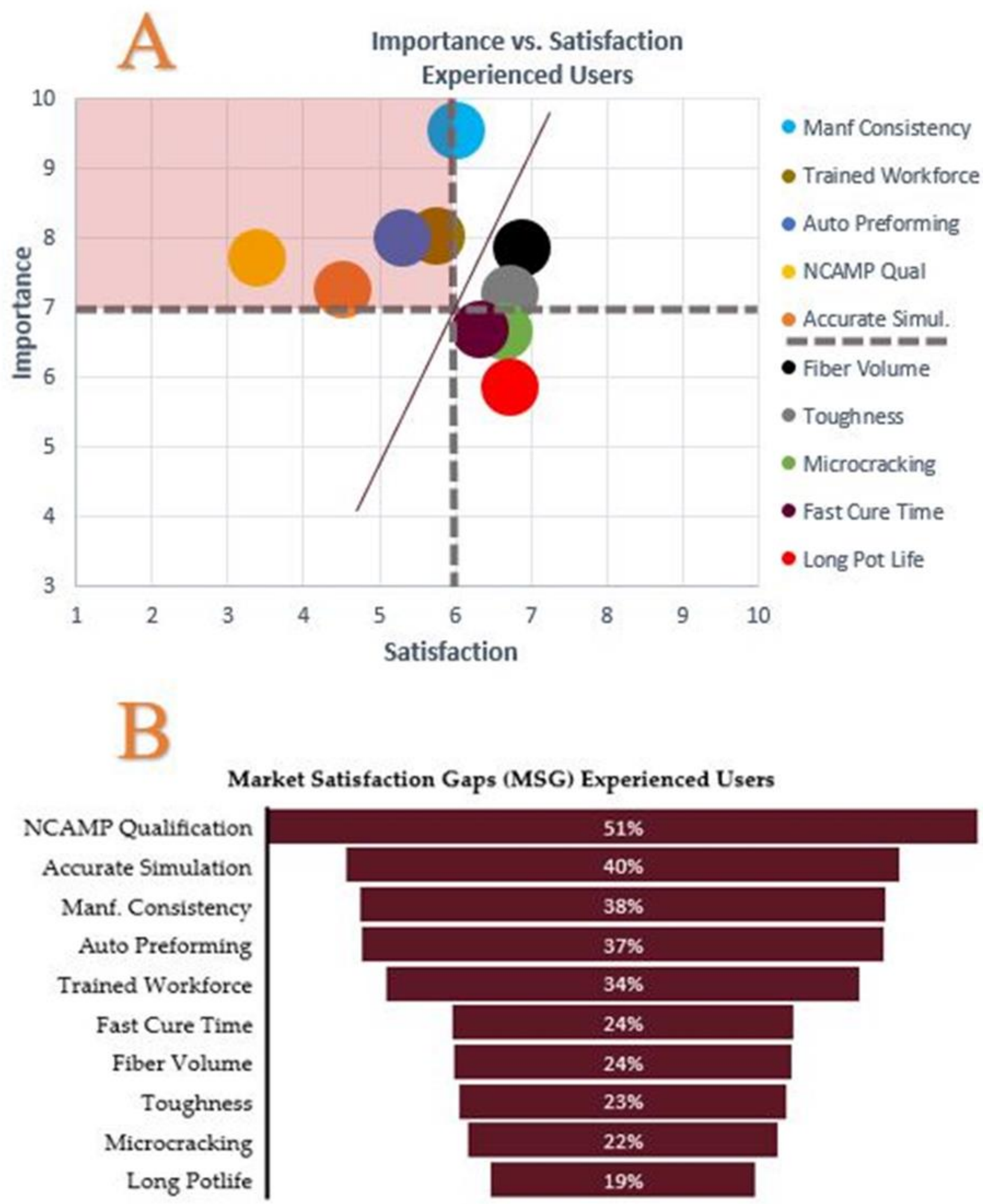

Figure 10. Data for experienced users of aerospace resin infusion industry

A) Importance vs. satisfaction plot for experienced users for aerospace resin infusion industry (Blue line is to aid the eye)

B) Industry satisfaction gaps for experienced users for aerospace resin infusion industry

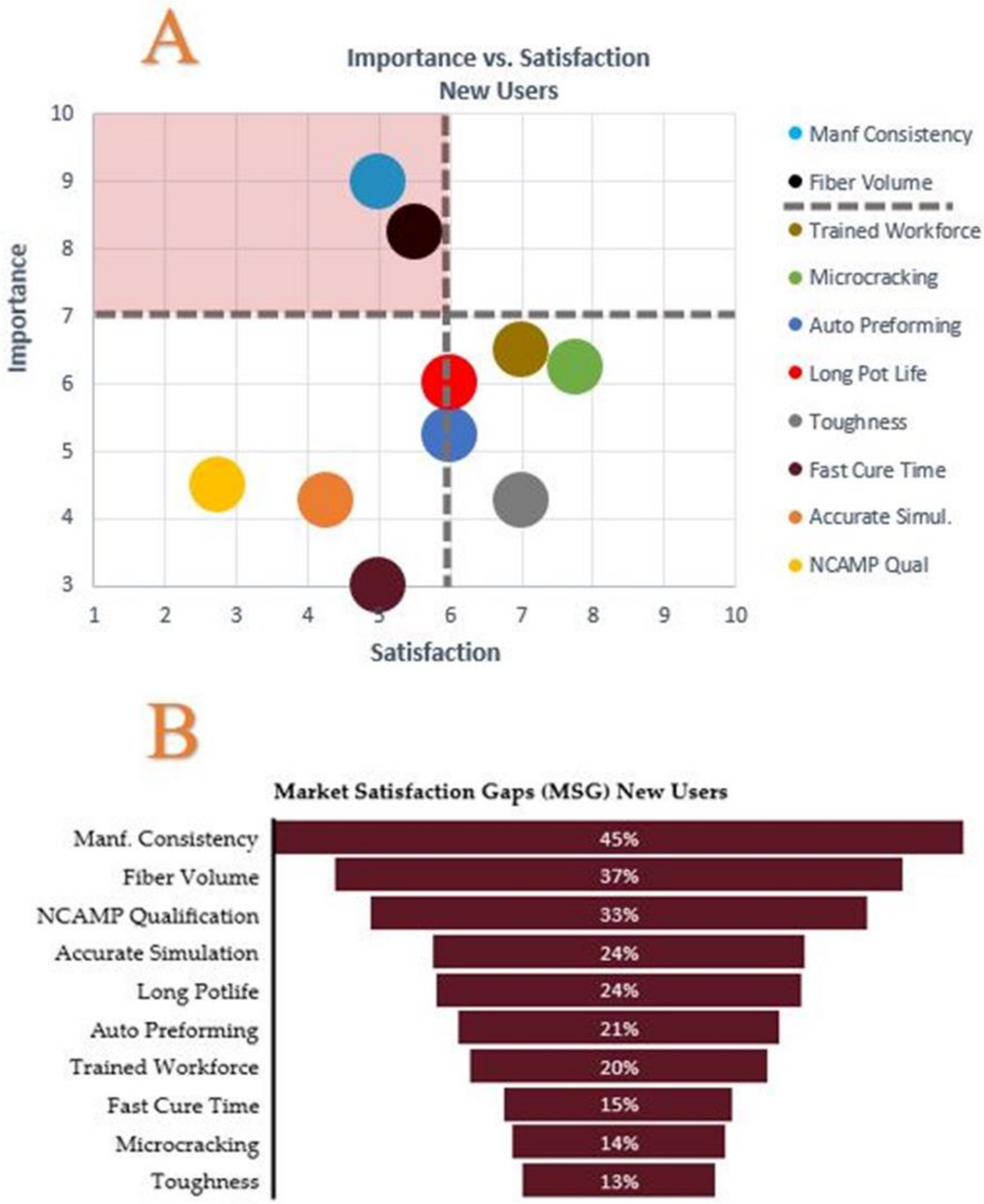

Figure 11. Data for new users of aerospace resin infusion industry

A) Importance vs. satisfaction plot for new users for aerospace resin infusion industry

B) Industry satisfaction gaps for new users for aerospace resin infusion industry

2.1.6 Machine solutions

The importance vs. satisfaction plot for machine solution providers (Figure 12A) shows they have few problem statements found in the top left quadrant. It can be difficult to identify why the importance vs. satisfaction plots between tier 1 suppliers and machine solutions are different as tier 1 suppliers are heavy users of the machine solutions.

Although the importance vs. satisfaction plot shows only one topic in the top left quadrant, the ISG (Figure 12B) plot highlights several areas above the 30% threshold that should be addressed: manufacturing consistency, automation of preforming, consistent fiber volume fraction, and NCAMP qualification. This shows how the ISG plot should be used in tandem with the importance vs. satisfaction plots and can uncover unmet needs.

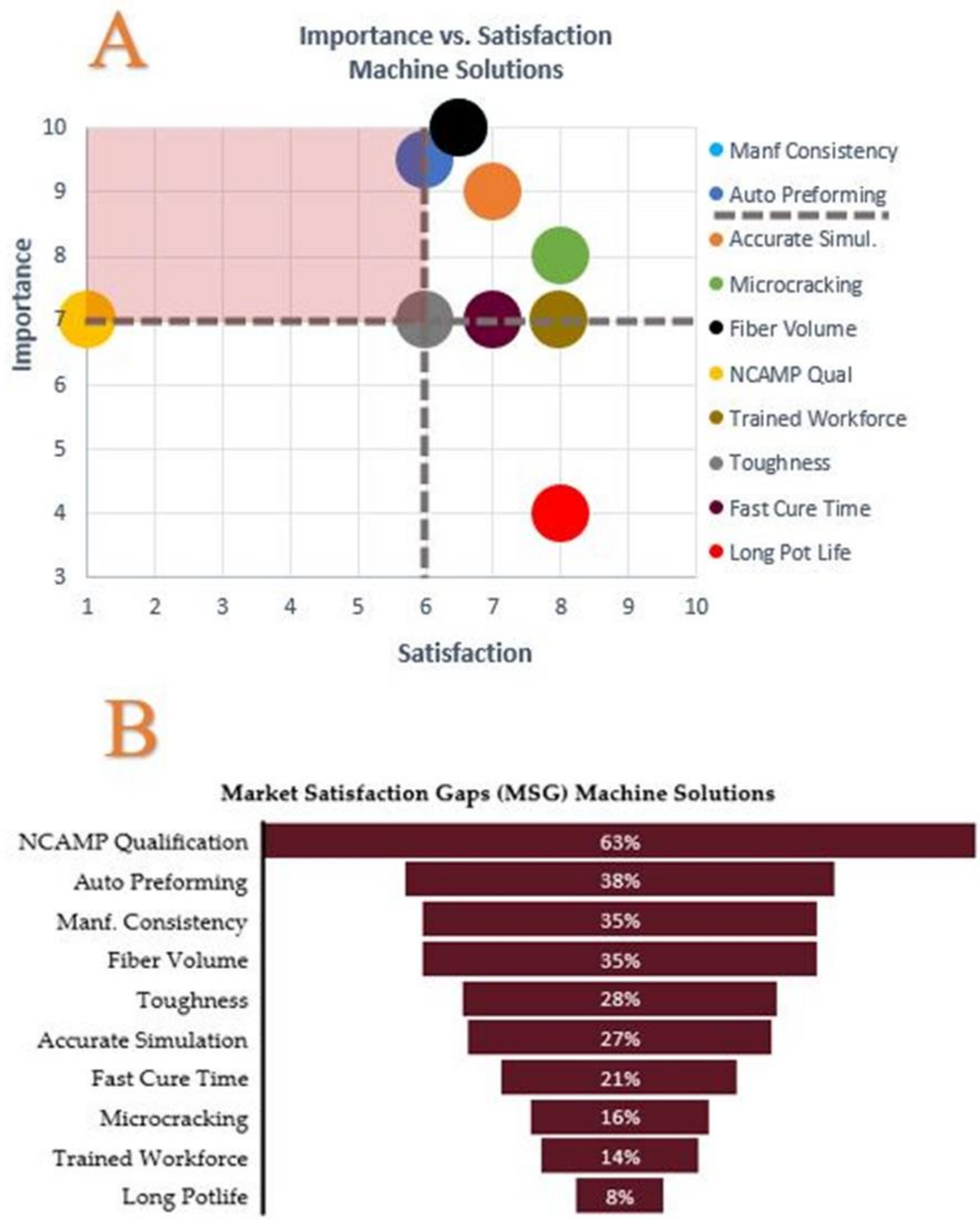

Figure 12. Data for machine solutions suppliers of aerospace resin infusion industry

A) Importance vs. satisfaction plot for machine solutions suppliers for aerospace resin infusion industry

B) Industry satisfaction gaps for machine solution suppliers for aerospace resin infusion industry

2.2 Targets and methods

The defining output for the NPB process is found in Table 3 and Table 4. The target and test method data were collected during preference interviews and are goals or targets to fully satisfy the industry for each of the identified problem statements.

Table 3. Targets and test methods identified for problem statements

Problem Statement	**Target**	**Test Method**
NCAMP qualification	Variation of fabric & resin, lower cost (equivalency), comprehensive database	More NCAMP entries
Manufacturing consistency	99% defect free	6-sigma DMAIC
Auto preforming	Prepreg *See Table 4 for quantitative metrics	Accuracy, quality, laydown rate, capital cost, flexibility
Accurate simulation	Accurate prediction	Drapability, resin flow, springback, 2D to 3D part, manufacturing.
Trained workforce	Local Workforce ready for technology transition	Training certificate
Microcracking	Toray T800S/3900, Hexcel 8552	Correlation between temperature, moisture, and microcracking.
Fast cure time	4 h (50% lower than EP2400 @ 8 h)	Tact & tool time
Toughness	Toray T800S/3900, SolvayEP2400, HexPly M21E	Fracture toughness ASTM D5528; ASTM D7905;
Long pot life	20 h (10 h @ 100° C Solvay EP2400) Improve 50%	Rheometer ASTM D3056
Fiber volume fraction	60% ±1-3%	ASTM D3171

2.2.1 Public material qualification database

The summary of the targets desired to fully satisfy the industry for a publicly available material qualification database are increased variation of fabric and resin, lower cost qualification, full physical data included in the material property report, entire plots of measured data (i.e., tensile testing) in the material property report, and various shapes tested.

The interviews uncovered a general satisfaction with the material in the NCAMP database but there was room for improvement. For an infusion process, there can be *many* different resins, reinforcements, and layups that could be included in the database. The overall desire would be to have a single resin with many different types of reinforcements, a single reinforcement with many different resins, and many different "typical" layups used. Having all this information in the database will make it easier for companies to choose a material system that best suits their needs for different applications; however, it is prohibitory to include all possible variants. Therefore, the most common material and resin systems should be a focus. It was made clear that larger companies will continue to perform their own internal qualification of material systems, but the NCAMP database is a starting point to these qualifications. Additionally, the NCAMP database will likely be most utilized by smaller to mid-sized companies. Producing NCAMP entries for resin infused materials is a quantitative test metric that can show progress.

The high cost and extensive time requirement for producing an NCAMP qualified material was repeated *many* times as a large hinderance. Interviewees believed the population in an NCAMP database will suffer because of the extreme cost and time commitment required, especially for the vast landscape resin infusion provides. Previously, there was little business case for companies to populate the NCAMP database with infusion materials due to the cost; this is changing as several companies are beginning the process to populate the NCAMP database with infused materials at the request of their customers. It was suggested that equivalency was the easiest method for lowering cost and time, especially for small changes in a system (i.e., a small change to the layup schedule).

Resin infusion has a plethora of possible process changes to produce the same output, and an equivalency program that is acceptable of variable processes would be helpful. There are >10 named infusion processes and there may be >20 other nuanced processes. This is another reason to fully populate the NCAMP database – a large population will allow for an easier equivalency program.

A possible list, but not all inclusive, for physical data to be included in the NCAMP database is unnotched tension, unnotched compression, in-plane shear, inter-laminar shear, open-hole compression, compression after impact, and fracture toughness. Additionally, the hot-wet testing was identified as a large cost burden and would be very beneficial to be included in NCAMP. Also, often only peak data is included for some of these parameters; it was suggested the full data collected during testing would be beneficial as sometimes peak data can be misleading or difficult to use for design.

Additional shapes beyond flat panels were also requested (i.e., T-shape stringers or bolted joints), especially to take advantage of the capability for resin infusion to unitize structures. Unitization of structures is very different than prepreg composites and can highlight a large value proposition for resin infusion.

2.2.2 Manufacturing consistency

The manufacturing consistency target identified was a 99% defect free production, as close to 6-sigma as possible, something the automotive industry can meet but is also a very aggressive metric. Although this is the desired capability for resin infusion, it was questioned what sigma value current prepreg can reach and was suggested to be a value of 3-4 sigma (a yield of 93.32%-99.38%). Resin infusion is expected to meet and/or beat the quality of prepregs after further development.

2.2.3 Auto preforming

The targets for preform automation are to meet or beat prepreg capabilities for accuracy, quality, and laydown rate and to lower cost and increase versatility. Table 4 shows more specific metrics related to the targets for automation of the preforming process and are values for current aerospace prepreg. Higher accuracy, higher quality, and faster laydown rate are directly comparable for prepreg vs. resin infusion. Lower cost and more versatility for automated systems are general targets for higher satisfaction – the extreme cost prevents small to mid-sized companies from purchasing, and the lack of flexibility makes it even harder.

Table 4. Specific targets for auto preforming

Topic	**Target**
Pick and place accuracy	±2 mm
Fiber direction	UD ±3°, fabric ±5°
Lay down rate	40-50 m2/h small course; 100+ m2/h large course
Fabric slitting tolerance	±0.005”
End effector tolerance (lap/gap)	±0.002”/±0.008”
Course-to-course tolerance (lap/gap)	±0.015”/±0.015”
End placement	±0.100” for up to 0.5” tapes; ±0.015” for 1.5” tapes

A lower cost solution was one of the most important topics for automation of the process. It is believed this information suggests the quality in automation is acceptable, but the real difficulty is the cost – it could be millions of dollars for a system. This prevents higher adoption for smaller companies, but there is a legitimate question if automation is required for smaller companies.

Programming automation systems is also difficult. It can require some trial and error and many engineering hours to program the system, nevertheless, handle multiple different types of preforms. An increased flexibility for the automated systems would help its adoption. Additionally, the heads of the automated systems limit what size of parts can be made (i.e., large heads and systems will struggle to produce smaller parts) further limiting the flexibility of the purchased systems.

There were some specific challenges for preform automation. Bulk, for example, is an issue during performing and is strongly influenced by the material choice and provider; similar materials from different suppliers can have different bulk factors. Bulk influences the final part fiber volume fraction, the wet out of the dry fabric during infusion, and the final mechanical properties. Similarly, different raw material suppliers and machine solution companies have differing mindsets on how to address stabilization of the dry fabric and preform during the automation process, whether spot welding/tacking or thermoforming. Current reinforcements have varied capability for automated preforming and the addition of thermoplastics/binders can heavily influence the final mechanical properties and compatibility of the reinforcement and resin.

2.2.4 Accurate simulation

Accurate simulation of the resin infusion process is a complicated, multi-faceted problem that can have many different possibilities: the infusion process, drapability of the dry fabric, resin flow as a function of cure, spring back of the part after removal from the tool, manufacturing inconsistencies, and using digital twin/thread. Above and beyond all the different parameters that can be simulated, the word *accurate* is difficult to quantify, within the industry and by our interviewees. It is proposed to work with NCAMP and the resin infusion steering committee to determine how to define *accurate*.

It was consistently suggested the inputs for simulation are difficult to produce, have no agreed upon methodology, and structures beyond flat panels perform poorly when simulated. Ultimately, the value for simulation lies in the ability to predict the above parameters prior to experiments but the reality requires too much effort and time to modify the simulation process to reflect the physical phenomena. This could become a major concern for resin infusion as the aerospace industry is continually moving towards more integrated digital design and process control. A standardization body, such as NCAMP, ASTM, SAE, etc., should dictate the appropriate process for collecting the input parameters.

Due to the struggles with using simulation, most of the interviewees decided to forego simulation but rather relied on process intuition build over years of laborious effort. A trial-and-error process is untenable if resin infusion intends to truly compete with prepreg, especially for large parts (i.e., wing box). Because of the breath of the capabilities for simulation, it is suggested a more narrowly focused new product printing process focusing on specific aspects for simulation should be conducted.

2.2.5 Trained workforce

The most clear and concise explanation of how to satisfy the industry with a trained workforce was to increase the knowledge base for users – to understand the "why". A broader knowledge base for technicians concerning how manufacturing issues affect final part quality is highly desired. To support this, technicians need more training about resin chemistry (pot life, cure, gel time), how layup impacts the infusion process, basic infusion techniques, and troubleshooting skills. Training programs to certify trainees, such as non-destructive inspection (NDI) operator levels, would help to bolster confidence in the skills of the newly hired technicians.

Additionally, having a local labor force that is ready on "Day 1" was highlighted by interviewees. This suggests large, national trainings institutes can be very useful and increased focus on specific geographic areas would also be helpful. As an example, local training facilities, whether 2- or 4-year colleges or government backed entities can use their resources to best facilitate a region-specific training. Further partnerships, both private industry and governmental, to help facilitate more training centers would help to satisfy the industry as there was consensus that more sites need to teach resin infusion. A quantifiable test method is a training certificate provided by the training facility, a common practice in the field.

Another desire for a resin infusion workforce is the availability of both technicians and engineers who are familiar with and can maximize the advantages of resin infusion. An example of the lack knowledge is manifest in composite parts not designed to best suit the wet out of the dry fabric, nor to take hold of all the advantages an infused part can afford (i.e., unitization of parts); it was even highlighted many prepreg composites are essentially "black aluminum", not nearly taking full advantage of the performance of composites. Therefore, more training for users about the specifics of resin infusion and the potential benefits will allow for better utilization of resin infused parts and better composite training in general will help to grasp the full advantages of composites.

One interviewee claimed the workforce need not expand due to the push towards automation, but the author disagrees. While it is true more automation will alleviate some repetitive motion tasks, it will also add complexity to troubleshooting issues, maintenance, support, programming, and add another specialized expertise to use the equipment. Thus, the transition from manual layup to automated layup will change the skillset required for technicians and engineers alike but not fully replace them.

2.2.6 Microcracking

Microcracking was identified as a problem statement for users of stitched resin infusion but was almost non-relevant for users performing resin infusion alone. During initial production, microcracking is unacceptable for resin infused parts, and it seems companies are satisfied with their ability to prevent microcracking; however, microcracking during the lifecycle of the composite parts is acceptable as prepregs exhibit microcracking during their usage and it has not limited their applicability.

An acceptable target for microcracking of resin infused parts is the current Boeing 787 Toray 3900 prepreg with T800S fabric or Hexcel 8552 prepreg. Testing resin infused parts for microcracking after thermocycling, up to 3,000 cycles was suggested; interviewees did not have a preferred method for detecting microcracks, as there are many different mechanisms and metrics to measure microcracking – one can measure directly the number of microcracks over the linear face by optical microscopy, the number of microcracks in a linear direction by electron microscopy, the number of microcracks in a square area by electron microscopy, or the overall length of microcracks in an image. Additionally, no easily defined metric for a “micro-crack” was found although Composite Materials Handbook (CMH-17) claims microcracks are within the range of 1-100 μm.

The correlation between microcracking, temperature, and moisture was suggested as a test method.

2.2.7 Fast cure time

Initially a problem statement of “infinite pot life and instant cure” was identified from the industry but it was decided to separate the probed parameters to test if the industry had preference for pot life or cure time. Overall, the cure time of Solvay EP2400 was identified as an acceptable metric and any improvement to the 8 h cure time would need to be significant (i.e., 50% decrease to 4 h).

The impetus for a faster cure time would be increasing the manufacturing rate. It was discovered during preference interviews that a reduced time on tool may be a more accurate test method than a faster cure time as the time on tool encompasses more than the cure alone. This would include time related to the layup, bagging, infusion, cure, and demolding. Another way to reduce time on tool would be a lower temperature cure as very slow heating rates are used to help lower residual internal stresses and control cure, but this would require a significantly lower cure temperature to move the needle on the technology. Additional tools can artificially lower the on-tool time but reach an asymptote as production facilities can only house so many tools.

2.2.8 Toughness

The toughness of resin infused parts was found to be a problem statement during our discovery interviews but was not particularly important during preference interviews. A blanket statement of "resin infusion needs to meet prepreg toughness" was too broad for our interviewees as only certain applications require a high toughness.

The targets for a toughness comparison are the prepregs used by Boeing or Airbus, Toray T800s/3900 with Solvay EP2400, Hexcel Hexply M21E, and Hexcel 8552. Additionally, it was suggested that resin infused parts can have a higher toughness compared to prepreg, whether through knit stitching of the dry fabric or through more complicated layups. It was also suggested the carbon/epoxy composites should try to attain the same toughness as thermoplastic composite parts, which are currently in the range of 4x tougher.

2.2.9 Long pot life

The original ask was for a resin to have an infinite pot life and instant cure; while this is still elusive, there are steps to be taken to reach this goal. A goal for the resin viscosity is 100 centipoise at room temperature; current aerospace grade resins are heated to ~ 200 °F, or more, to reach the low viscosities (100 cP) required for infusion. Therefore, if a resin has a long pot life and a viscosity acceptable for infusion at room temperature, the *snap cure* can be approached because the resin chemistry can be reactive enough to cure quickly. Environmental, health, and safety concerns do need to be addressed for controlling large exotherms. Novel resin systems are broadening the processing window but do not approach infinite pot life and instant cure.

A metric for improvement in the pot life is 30-50% increase in pot life to "move the needle" but the collected responses showed the current resins are acceptable: Solvay EP2400 at 2 h. Experienced users claimed the infusion process is poorly designed if > 2h is needed for infusion.

2.2.10 Consistent fiber volume fraction (FVF)

The comments collected during the preference interviews showed consensus that a consistent fiber volume fraction (FVF) is very important throughout the entire part as the FVF variability affects design allowables. Some interviewees explicitly said that users equate a high and consistent FVF with performance. There was not a consensus as to the exact FVF ratio, some said 60% ± 3%, some said 65% ± 2%, and some said unidirectional (60%) can have a higher FVF than woven fabrics (50-55%). The Clean Sky 2 project aims for a FVF of 60% ± 3%.

Additionally, there was some concern whether a vacuum assisted resin transfer molding (VARTM) process can prevent bridging in 90° corners (such as a T-section) as it only relies on atmospheric pressure. It was expected a closed process, such as resin transfer molding (RTM), could have even better FVF consistency than prepreg and would not have issues with 90° corners. Measuring the FVF consistency, especially for complicated geometries, poses a challenge and no solution was offered.

An experienced user was adamant that a consistent FVF was the incorrect problem statement for resin infusion. They suggested infusion can easily hit the FVF targets with high consistency and that resin infusion can outperform it's prepreg counterparts due to the design flexibility and the layup schedule.

A consistent FVF is closely tied to the preforming automation process – a poorly developed preform will have issues during the infusion and have poor FVF. Please see the Auto Preforming section for further discussion.

3 Conclusion

To our knowledge, this is the first time the New Product Blueprinting (NPB) Process has been utilized in academics and it has uncovered and quantified the top 10 problem statements related to resin infusion for commercial aerospace applications. Quantitative targets and test methods have been identified and the Mississippi State University Advanced Composite Institute (ACI) will use these data to direct our future research. Further use of this process will aid in identifying specific problem statements for simulation; this is important as the simulation capabilities were shown to be very important but still highly unsatisfied, showing the existence of a significant industry satisfaction gap that is ripe for research.