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Remanufacturing Cleaning Process Evaluation, Comparison and Planning

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REMANUFACTURING CLEANING PROCESS

EVALUATION, COMPARISON AND PLANNING

A Thesis

by

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ABSTRACT

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This thesis aims to combine previous research on remanufacturing cleaning processes and applications into a single decision-making tool, in the form of software, which a remanufacturer can use to find a cleaning system that matches their specific demands. This thesis will provide an in-depth review of each cleaning process, the chemicals used in those processes, and the contamination types for which they were developed. This research also provides evaluation and comparison that assists remanufacturers in designing their cleaning systems. Finally, there will be a description and demonstration of the software. The ultimate goal is to find correct cleaning process to remove a variety of contaminants from metal substrates with high efficiency.

DEDICATION

In the two years' graduate study, love and encouragements from my mother Nezihat Yagar and my father Orhan Yagar have always been surrounding me. Also, support and help from my advisor Dr. Jianzhi Li and friends at UTPA make it possible for me to graduate. Thank you for your inspiration and I love you all! And finally, thanks to my parents and numerous friends who endured this long process with me always offering support and love.

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CHAPTER I

INTRODUCTION

1.1 Background

1.1.1 Background of Remanufacturing

In an era where concern for a healthy environment co-exists with an ever-decreasing amount of raw material resources, businesses have to do more with less. With the cost of materials and waste disposal on the rise, industries turn to material productivity initiatives in order to maintain profits. These initiatives have included processes such as material substitution and recycling, but the greatest opportunity to save raw materials and manufacture like-new products lies with re-manufacturing. Though currently used in only a few industries, remanufacturing is becoming more popular and will soon become a widely accepted cost-saving practice [1].

Remanufacturing has been defined by Seitz as “the transformation of an end-of-life product into a product with an ‘as good as new’ condition” [2]. Remanufacturing returns a used product to like-new condition; it is a process of recapturing the value added to the material when a product was first manufactured. The benefits of remanufacturing are that it uses a smaller amount of material and consumes less energy. This process also decreases production cost. The revenue that remanufacturing generates from waste combined with environmental advantages could potentially make the process a major contributor to sustainable development and movements. In many countries in Europe as well as the United States, remanufacturing demands are increasing due to the benefits of low energy, material and worker needs [3]. Remanufacturing is used for many different types of damaged products, which include defective produced products, products damaged during transportation, commercial returns, warranty goods, end of use products and end of life products. These used components are remanufactured to ‘‘as-new’’ or upgraded status and returned to the market [4]. The process of remanufacturing typically occurs as shown in the figure below. Returned parts from the customers have to be collected. After collection, the parts are disassembled. Depending on the characteristics of the material and contamination, a suitable cleaning process is applied to the part. After the cleaning process, the results are inspected and the fourth step of the process begins. The parts now need a reconditioning step, during which a finishing process is applied to the parts. After cleaning and reconditioning, parts are re-assembled. The process concludes with a last test before being sent back to customers. Parts are tested to make sure their condition is like new and that they will have a long life cycle. If the system results are not good enough and the part fails again during the test, parts are sent back to remanufacturing depending on their condition. Products can be remanufactured two to four times.

Figure 1 - Phase in the Engine Remanufacturing Process

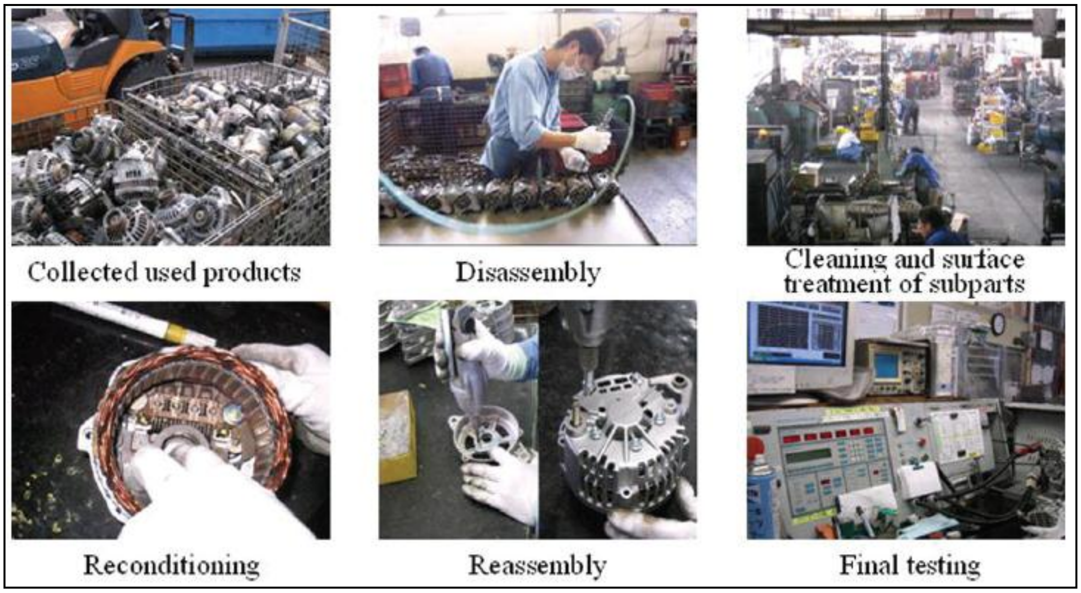


Figure 2 - Phase in the Engine Remanufacturing Process with Pictures [5]

In some cases, it is determined that the part is broken after the cleaning process or was received in poor condition. In this case, the part has to be recycled and used as raw material for manufacturers.

A common challenge for all the remanufacturing processes is that parts are received under different conditions and with different contaminants. These varied contaminants may differ in their composition, structure, density, and thickness. Additionally, received parts do not all share the exact same condition, which makes determination of these parameters difficult. Choosing the correct process may be difficult given varied parameters, but is vital for the success of the remanufacturing process.

1.1.2 Cleaning Process Problems

The cleaning process is one of the most important remanufacturing operations for remanufacturers. Rick Hammond, Tony Amezquita, and Bert Bras [6] conducted a research survey of remanufacturers that proved the importance of the cleaning process. Survey results are shown on the figure below. As the graph illustrates, 29% of the remanufacturers' highest expense is the cleaning process. The cost of the cleaning process is a significant factor for remanufacturers.

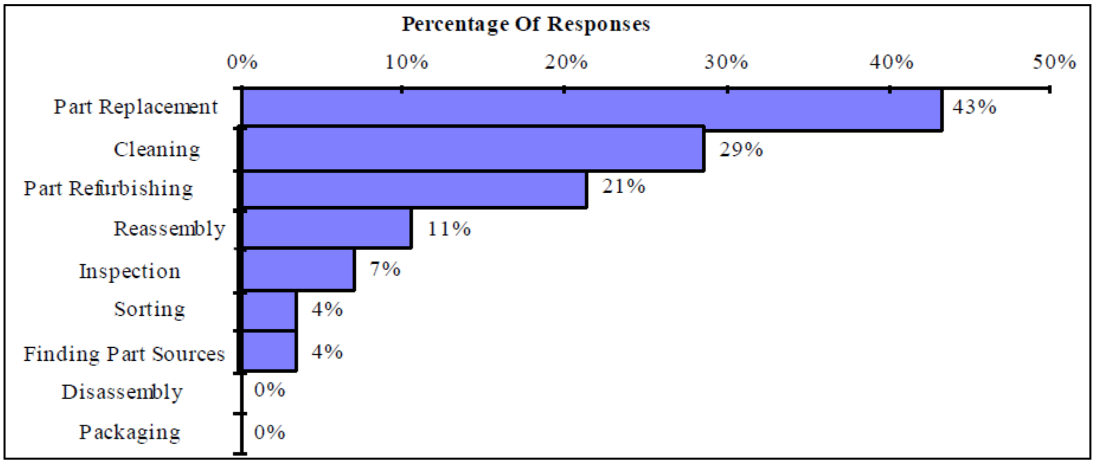


Figure 3 - Responses to question: Which is more costly in remanufacturing? [6]

Because the cleaning process represents such a great cost to the remanufacturer, and because this step is so critical to the remanufacturing process, it is crucial that the correct cleaning processes are chosen. Most cleaning processes are designed based on the structure of the contamination and the type of the material the product contains. Energy consumption, general cost of the machine, system load capacity, cycle time, productivity and efficiency are also important considerations in designing the cleaning process. Hence a successful value recovery operation requires careful consideration of four factors: environmental issues, energy consumption, system cost, and cleaning result. Remanufacturers use these factors, which are described below, when making system design decisions.

Environmental damage that occurs as a result of waste management problems is important because of the extremely high cost of managing the waste. Remanufacturers have to select the process with the lowest environmental emissions. However, sometimes it is not possible to design a process with low emissions given the desired cleaning result and contamination type. In that case, the waste from the remanufacturing system has to be treated before discharge. This treatment creates an extra cost for the remanufacturer. If the system has smoke or dust emissions, then a filtration system has to be used. Different types of filters can help the system to hold dust, and dust collectors can save the dust from contamination. Although it is important to monitor and control dust and smoke emission levels, filtering and cleaning will result in an extra cost for remanufacturer.

Energy consumption is the main problem for manufacturers and remanufacturers now. Since fossil fuel prices started increasing dramatically, a system's energy consumption has become one of the most significant contributors to cleaning costs for the remanufacturer. Energy consumption is just one part of the overall process cost. Process cost also includes the cost of cleaning medias, workers, system maintenance, and labor. These parameters are another significant factor in a remanufacturer's system design.

System cost is the last main consideration for the remanufacturer. System cost is a fixed rather than variable cost, so when the process cost is determined per part, the system cost is not considered. However, system costs are important for determining the overall cleaning cost and types of systems that can be selected by remanufacturers according to its budgets available. Selected system can also result in different batch size, chemical type, cycle time, operator number, and energy consumption, which directly affect the calculation of the cost of cleaning. All these parameters are dependent on the features of the system as chosen by the remanufacturer.

As mentioned, budget and cleaning cost are important for the remanufacturers, as are the results of test cleaning and the particular goals of the project during the cleaning stage. Industry standards help to determine equipment recommendations. The methods used to evaluate cleanliness are almost as diverse as the industries that clean, and some facilities use several methods. These may include visual inspection with or without a black light, white glove tests, and water break tests. In many facilities, successful implementation of a subsequent process such as plating, coating, or welding is an important evaluation tool. Clean room applications typically measure particle counts. Another test is based on the thickness of contamination at the end of the cleaning process. Many companies use the process of purchasing a new cleaning system as an opportunity to review their cleaning practices and standards and to further refine them [7]. The cost for the cleaning result is the major determining factor for system decisions.

This study exposes many problems concerning cleaning results and the cost of the cleaning. Hence, choosing a cleaning method that can both avoid these problems and clean products with a high level of efficiency and low emissions is enormously beneficial to remanufacturers. This thesis contends that comprehensive analysis of modeling on existing cleaning process can provide a support tool on process planning and optimization for remanufacturers. The following section will introduce the general cleaning mechanism, parameters for each process, and cost of the cleaning per part.

1.2 Cleaning Processes

1.2.1 Cleaning Processes Types

The cost of cleaning has been identified as one of the highest contributors to the overall cost of remanufacturing. The characteristics that affect the cleaning system are the type of dirt, size of the part, number of parts to clean, and the composition of the parts [8]. On the other hand, many different processes and machines have been developed to accomplish the task given the material to be cleaned, features of the part, quantity of parts, and the method of handling the workload. Methods of cleaning range from manual to automatic, batch to continuous, mechanical to chemical, each with many variations from which to choose [7]. To decide which process to use for a given application, we must first realize that each method was developed, often by trial and error, to solve a particular cleaning problem using the technology and materials available at the time.

Significant changes and advances in industrial cleaning that we see today were mandated by legislation as much as they were motivated by the technical need for improved cleaning performance [7]. For most of the cleaning applications that we may encounter, there exist one or more processes that will satisfy all the requirements. The choices may be obvious given the cleaning model, but more often the decision requires a thorough analysis of the requirements confirmed by testing in the lab. As we gain experience, it becomes easier to narrow the choices to be considered. The following sections will describe the main cleaning processes for engine parts.

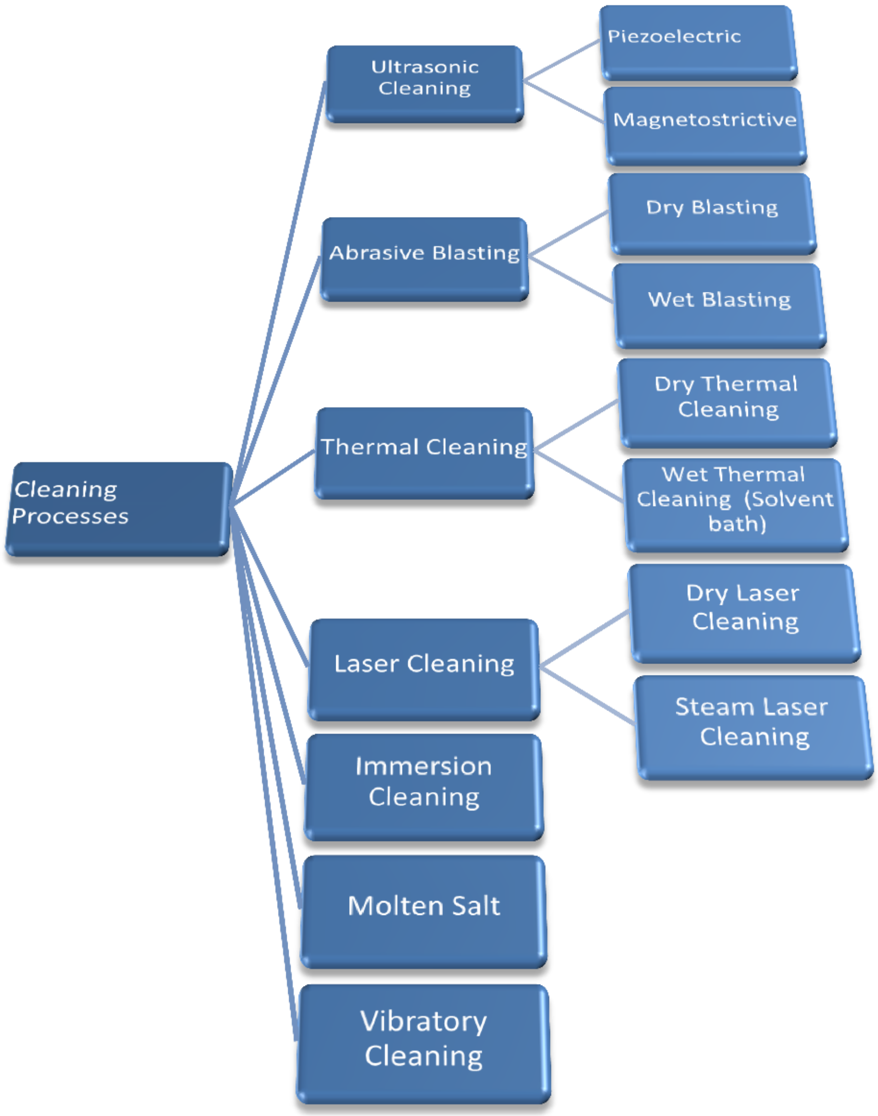


Figure 4 - Figure Engine Cleaning Processes

1.2.2 Cleaning Chemicals Structure

As with contaminants, we can group the chemicals used for industrial cleaning into categories for different processes. There are two major groups of cleaning chemicals, organic (solvent based) and inorganic (water based or aqueous) [7]. These major categories are shown in the chart below.

Organic			Inorganic	
Chlorinated Solvents	*Petroleum Solvents*	*Miscellaneous Organics*	*Alkaline Detergents*	*Acidic Detergents*
Trichlorethylene	Mineral Spirits	Alcohols	Alkalines	Phosphoric Acid
Perchlorethylene	Kerosene	Glycol Ethers	Caustics	Hydrochloric Acid
1,1,1 Trichloroethane	Naphtha	Methyl Pyrrolidone		Hydrofluoric Acid
Freons®	Stoddard Solvent	Ketones		Nitric Acid
Methylene Chloride	PD680	Terpenes		
n-propyl bromide		Organic Acids		
		Vegetable Esters		

Table 1 - Cleaning Chemicals [7]

In general, the organic types of solvents are removes organic soils and inorganic chemicals are most effective against inorganic contaminants. There are some exceptions to this generalization organic solvents will remove inorganic and particulate contaminants if the soils are being held on the part by oils or grease [7]. Water can be uses with inorganic chemicals to produce an effective cleaner for oils or grease, and some processes require de ionized water for wander walls physical power of water. Also chemical selection is important matter to be considered for its hazardous effect on the workpiece. Chemical effectiveness is really important that completely removes the contaminant, but if the part being cleaned is damaged in the process, this is not acceptable. Therefore, correct type of cleaner and has to test at the laboratory before using in certain type of cleaning processes.

Chemical Cleaners: Chemical cleaners can be categorized by solvents, alkalines, acid and caustic cleaners. They are implemented in different cleaning processes depending on the contamination type. The following figure clarifies the chemical type and affected contaminants.

Contaminants	Cleaning Agents			
	Alkalines	*Caustics*	*Acids*	*Solvents*
Oils	X	X		X
Grease		X		X
Wax		X		X
Chips	X	X		X
Dust	X			
Rust		X	X	
Scale		X	X	
Smut	X	X	X	
Fluxes	X			X
Paint		X		
Salts	X		X	
Buffing compound	X	X	X	X
Drawing compound	X	X	X	X
Lapping compound	X	X	X	X
Fingerprints	X			X
Silicones	X	X		X

Table 2 - Applicable Cleaning Agents for Various Contaminants [7]

A chemical cleaner's effective area is important for the system design. Along with system selection, chemical selection is also decisive in remanufacturing plant design. The correct type of chemical has to be applied with the cleaning process for high efficiency cleaning results. Therefore, specifications of chemicals are critical. The following section will introduce different chemical structure characteristics and effective area.

Alkaline Cleaner Characteristics	*Choice Relationship*
High alkalinity pH 11–13.5	Noncaustic sensitive metal processing only. Ferrous, stainless, and yellow metals. Composites.
High alkalinity (buffered) pH 10.5–12.5	Multimetal lines ferrous/nonferrous.
Low alkalinity pH 6–9	Nonferrous, aluminum, zinc, also effluent sensitive or restricted cleaning operations.
High-foam surfactants	Static tank cleaning, immersion systems, and spray wand nonrecirculating systems.
Controlled-foam surfactants	Agitated immersion ultrasonic, turbulator.
Low-foam surfactants	Spray cleaning and recirculated systems.
High temperature 140°F and above	Aged and oxidized soils of a waxy nature, heavy accumulations and short process contact time.
Medium temperature 120–140°F	Controlled soils. Light to heavy accumulations. Short to medium contact time.
Low temperature 90–120°F	Light to medium soils. Typical for medium contact time.

Table 3 - Alkaline Cleaners Characteristics [9]

Solvent Cleaners: Since cleaning processes started, removing of oil and grease-bearing soils, the use of organic solvents accepted as one of the most common cleaner. In most of the chemical cleaning process, solvent cleaners are used and also automotive parts remanufacturers are frequently use solvent cleaners.

The most common solvents used for oily soil removal have been petroleum-based solvents such as kerosene, mineral spirits and naphtha. Other solvents, for example toluene, methyl ethyl ketone (MEK), methyl pyrrolidone (NMP), acetone, alcohols, etc. are employed for more difficult-to-remove contaminants such as printing ink, resins, varnish, and so forth [7].

Alkaline Cleaners:

Alkaline cleaners are widely used for the removal of oils, grease, particulates, water-soluble soils and complex soils from metals, plastics and ceramics. Alkaline fluids can prepare metal surfaces for plating or painting [7].

Alkaline cleaners has strong chemical structure, therefore they are used part has to be rinsed in de-ionized water. Alkaline cleaners require high temperature for their highest effectiveness and remanufacturing process has to be designed based on this factor. Alkaline cleaners' effectiveness is higher than most of the chemical cleaner because they are clean the workpiece with chemical and physical action.

Acid Cleaners: Most remanufacturers select the cleaning design based on alkaline fluid cleaners. If remanufacturers have the significant problem has to be solved by the use of an acid cleaner, only on that time remanufacturers use the acid cleaners. Acid cleaners are highly effective on the metal surface and reaction speed is higher than other type of cleaners. Another significant problem with acid cleaners is reaction speed. Acid cleaners have really high reaction speed and this cause the defected workpiece problem for remanufacturers. Selected acid has to be tried in the laboratory before system is designed.

For example, while heavy rust and scale can be cleaned using a heavy-duty alkaline solution, an acid formulation can usually perform these operations faster. Further, if some surface preparation, such as etching, is required, an acid-based detergent would be the fluid of choice. Typical examples would be the removal of rust or heat scale from steel, stainless steel passivation, and brass and aluminum brightening [7].

When acid cleaners are used, the cleaning equipment must be constructed of materials resistant to the acid. As mentioned before, they are strong and effective cleaners. Another significant problem with acid cleaners is environmental problem of acid cleaners. After used on workpiece, workpiece must wash and, wastes of acid from cleaning and wash water have to send water plant to treat it.

Caustic Cleaners: Another good cleaner for remanufacturers is caustic cleaner and it is involving the removal of oil, grease bearing soils, rust and scale, the use of organic solvents has long been an accepted cleaning process. Use of caustic cleaners and soda is more effective for scale and rust cleaning processes or high strength carbon removal and paint cleaning.

Caustic is typically used to clean membranes fouled by organic and microbial foulants. The functions of caustics are hydrolysis and solubilization. One typical caustic soda is NaOH, which can be used to effectively remove all polar substances. Another typical caustic cleaner, sodium hydroxide, is employed for more difficult-to-remove contaminants such as rust, scale, resins, varnish and strong type of contamination [7].

1.2.3 System Design and Cleaning Parameters

Remanufacturing processes utilized in different industries can bear some similarities although these industries use different manufacturing technology, material, and assembly methods. Remanufacturing processes change from one industry to another, which alters the whole remanufacturing process line. For example, the auto remanufacturing industry usually employs aggressive processes for part cleaning such as liquid based cleaning process to remove oils, greases, carbon deposits, and coating. As such, special processes used in auto remanufacturing must be specifically discussed.

Figure 5 - Cleaning Process Parameters and Performance Measures

Remanufacturing process line designs and cleaning processes will be studied in the current research. Cleaning process parameters and performance measures were designed in Figure 5, and summarized as follows:

Contamination Type: Cleaning process shows high effectiveness on certain types of contamination. Therefore contamination type has to be determined before the system is designed.

Contamination Level: After contamination type is determined, thickness and concentration of the contamination has to be determined. Contamination level has critical importance for cleaning system settings and design.

Cleaning System Type: Cleaning system type is the one of the significant factor in system design. Contamination type, level and material must all be considered with chemical, physical or mechanical chemical type selection.

Processed Material Type: Type of material is also important to the cleaning process. System temperature, pressure, and chemical type selection are based on this parameter.

Cleaning Chemicals: Chemicals show different effectiveness on different types of contamination as mentioned before. Therefore, it is an important parameter of cleaning process flow design.

Temperature: Temperature has to be fit for material type, chemical efficiency, salt melting point, surface contamination melting point, and interior cleaning of the part. These factors have to be considered when determining system temperature features.

Cycle Time: Cleaning cycle is dependent on cleaning process and contamination structure. Cycle time is a critical factor when determining cleaned product number on daily basis. With this information, a system payback plan can be designed.

Efficiency: With each system cleaning model, system efficiency can be determined. With this information, the highest cleaning result can be found. Other significant factors must be determined first, so that the efficiency result can be more accurate and acceptable.

System Type and Number of Workers: Designed system can be automatic, semi-auto and manual. According to the system type, workers may be needed. Also, certain system types may require additional training, including intensive operator training on different types of software.

System Energy Consumption: Each system has an energy consumption model based on the cleaning area. Contamination type and thickness are also factors when creating an energy consumption model.

Total Cost per Part: After the part cleaning process is selected with the energy consumption model, worker number and chemical consumption are determined. With this information, each part's cleaning cost can be determined.

System Cost: After all the factors are determined, system cost can be calculated based on system design. A company might not have a sufficient budget for the best cleaning process, or the payback period might be extremely long depending on the remanufactured part demand. Therefore, system cost is one of the most significant factors for remanufacturers.

Emission Level: As mentioned before, environmental waste and cleaning has one of the highest costs for the remanufacturers. Depending on country and/or state policy, system waste parameters have to be maintained at a certain level. Environmental processes also include extra costs for the remanufacturers. If the manufacturer does not comply with state or federal policy, punishment may include extensive fines. Because of these additional costs, emission level becomes one of the most significant and important parameters of system design.

1.3 Problem Statement

In literature, it is nearly impossible to find a comprehensive study of the multitude of cleaning processes available to manufacturers combined together. The vast majority of the research focuses on a single cleaning process, or several cleaning processes for a single application. In the mean time, a lack of understanding of processes and comparisons between them causes significant problems for manufacturers and remanufacturers. Their planning of cleaning systems, and therefore the optimization and cost saving measures, are impacted by these delays and the general lack of resources. In this study, there are four major goals:

1- Provide a comprehensive in-depth analysis of the all applicable cleaning processes. Process factors are determined for each based on the general cleaning design. Energy consumption, cleaning result, and environmental factors are verified in this study.

2- In order to develop the most suitable cleaning processes, manufacturers must also have a good understanding of contaminants. This study will therefore describe the main types of contamination and sources of that contamination. This study also applies contamination types to particular remanufactured parts.

3- A variety of chemicals are being used in cleaning processes, and we need to develop a clear understanding of their effects on the work piece, their cleaning effectiveness, and the environmental issues that may arise during the cleaning. This study will determine the risk and benefits for each type of chemical.

4- Based on a model of cleaning processes, this study will provide specific support based on the typical part that is being manufactured. That means designing, planning, and optimizing the process based on provided models.

CHAPTER II

COMPLETE REVIEW OF CLEANING PROCESSES AND CONTAMINATION SCIENCE

2.1 Cleaning Processes

2.1.1 Cleaning With Abrasive Blasting

Blasting parts with corrosives is an effective way of removing contaminants from the surface. The contaminant removed might be dirt, soluble salt, carbon, oxidation, paint, gaskets, rust, ash, or even a layer of the part's surface [10]. This system includes both wet blasting and dry blasting types. The typical dry blast unit can use sand, slags (coal, copper, iron or nickel), minerals (garnet), metallics (aluminum, steel), glass, ceramics, sponges, plastic pellets, natural products (rice hulls, nut shells, corn cobs, starch grains), natural oxides (silica), carbons oxide (ice blasting), or aluminum oxide grit [11][13]. When the system is designed for wet abrasive blasting, the nozzle type is changed. The typical wet blast unit can use water with different pH levels, sand, mild alkali cleaners, detergents, dilute acids, weak alkalis, strong alkali cleaners (caustic soda), or baking soda granules [12][13]. Sometimes, dry abrasive blasting nozzle types can be adapted for wet abrasive blasting processes. Silica sand is commonly used for abrasive blasting in both dry and wet abrasive blasting systems [14].

Methods of applying abrasive materials can be segregated into two distinct types of procedures: dry and wet [15].

Dry Blasting: There are two methods used for dry-blast cleaning; mechanical blasting and air pressure blasting [15]. Dry-ice and sponge blasting methods are newer methods which are discussed under the dry blasting method.

Mechanical Blasting: A mechanical blasting system is used with cabinet type equipment. The system works in automatic and semi automatic modes [16]. The cabinet houses have blast wheels to apply the abrasive to the workpiece with centrifugal force. The wheel position provides maximum coverage and high efficiency of the blast pattern in consideration of the workpiece design. Different types of wheels are designed to have greater efficiency depending on the design of the workpiece. Generally, abrasive velocity (≈250 feet/sec) and volume of abrasive are the most important settings for higher working rate and cleaning result [15][16]. Mechanical blast equipment is generally used with medium to high production applications. The biggest advantages are that the system does not need penetrated temperature slope or increase in mass of the waste [17]. The pellets are reused and metal pieces taken out from inside the pellets easily. Prototype systems have hand-held suction, sand blaster nozzle and portable air compressor and are used for outside cleaning. This prototype system was utilized for testing various pellets, sand, and metal grit particles.

Air Pressure Blasting: Air pressure blasting uses compressed air to apply the abrasive to a surface. Air pressure blasting uses either direct pressure or an induction method that may utilize the siphon or gravity method as follows [15].

Direct Pressure: This system is used by moving abrasive from a pressurized container to a blast gun. The compressed air is piped to the blast gun of the pressure vessel. Air pressure reaches around 80 to 90 psi with the pressure abrasive point on workpiece. Direct air pressure blast cleaning machines can be used separately as portable units or it can be in cabinets or blast rooms [15].

Induction-Siphon Method: The blast gun equipment is also used in this method. Compressed air goes through the gun over the abrasive hose and creates a vacuum effect in the hose. It then induces the abrasive into the gun nozzle with the compressed air [16]. The abrasive speed is created by air pressure and it passes through the blast nozzle but does not reach the full velocity of the compressed air stream [14]. The velocity of the abrasive leaving the nozzle is approximately 60% less than direct pressure machine. Induction-siphon systems are used in a wide range of hand operated abrasive blasting cabinets. This system needs highly-trained workers [15].

Induction-Gravity Method: Induction gravity and siphon system working method is very similar to previous systems in that a gun is used to mix air and abrasive media. In the induction gravity system, however, the media is going to the gun with gravity from overhead storage [16]. The air system enters the gun at that point where the abrasive is creating a partial vacuum with the weight of the gravity. Rapid extension of the compressed air gives final speed to the abrasive [15]. The induction-gravity system is not widely-used in industry. Although they can be integrated for continuous systems as a cleaning step, they are usually designed only for specialized application with well-trained workers.

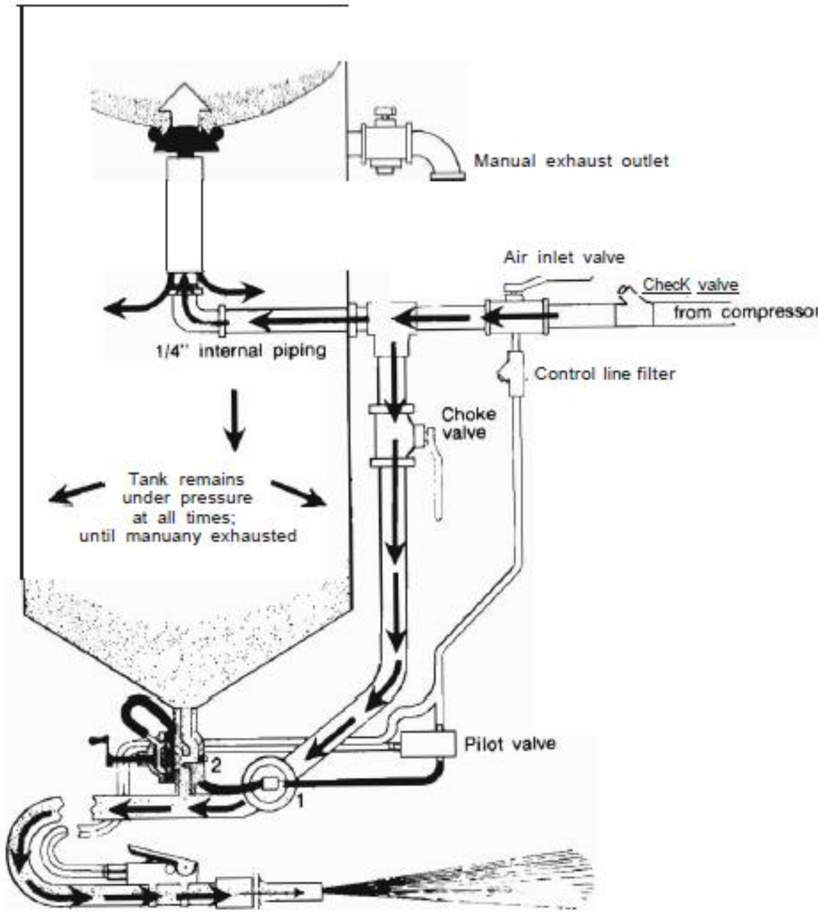


Figure 6 - Portable Blast Cleaning Unit [16]

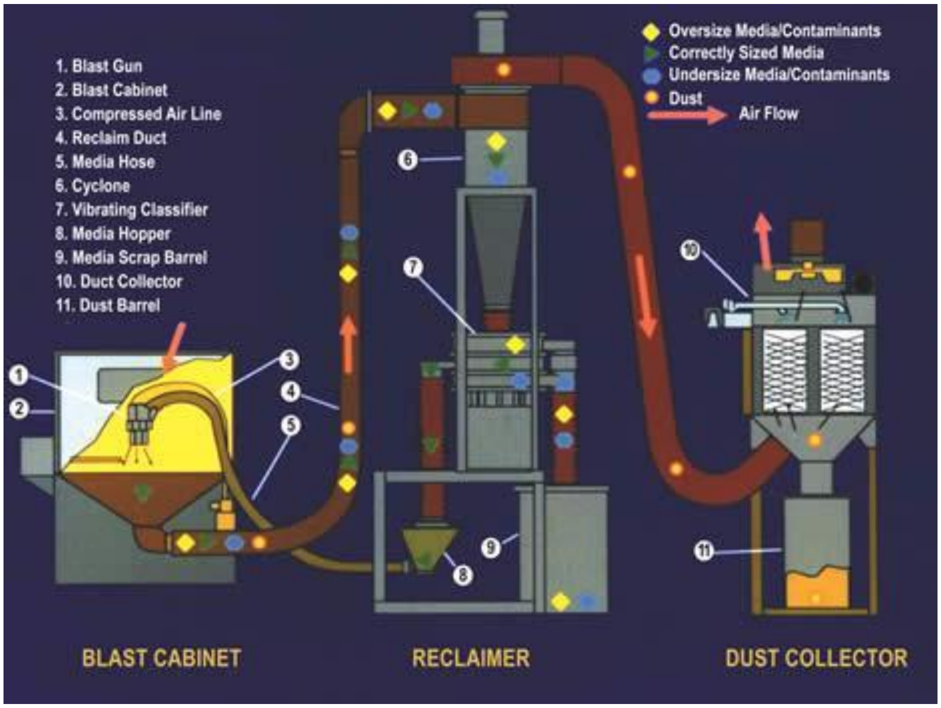


Figure 7 - Automatic Abrasive Blasting Cleaning Schema [18]

Dry-Ice Blasting Method: The system of dry-ice blasting is based on thermal and kinetic energy input. The thermal energy affects contamination during the cleaning process when the pellets hit the contamination and surface. After pellets hit the surface, the combined effect of the temperature and the pellets effect is to decrease the elasticity and shrink the coating. The thermal effect dissolves the coating when the energy is exceeded. The coating chips off when energy is transmitted to the coat and cleaning starts with this step. In the mean time, the kinetic energy of dry-ice pellets and air stream power significantly impact removal. When using a high performance round nozzle, a jet pressure of 12 bar and an air stream volume of $11m^3$/min, impact forces of the jet in dry-ice blasting reach maximum values of 150N. The departure velocity of the particles can assume values of up to 300 m/s [19]. Contamination removal systems are designed based on thermo and mechanical effect. When thermal and kinetic energy are both considered as a factor of the removal effect, thermal effect represents 60% of the cleaning process and kinetic energy has the other 40% of cleaning process. In the blasting nozzle, the carrier gas reaches almost the speed of sound which accelerates the pellets to speeds of 180 to 330m/s. Dry ice is solid CO2, i.e. gas cooled to approximately -78°C [20]. The cleaning processes are divided into three groups, which are machine, pellet, and process parameters. Machine parameters are based on the system specification, including hose diameters, type of nozzle, and pellet feed, which are considered the main factors of the system and machine used for the cleaning process. Pellet parameters are selected based on contamination and material type, therefore density, hardness, dimensions and CO_2 content are considered the main parameters. Process parameters are air pressure, flow rate, temperature, jet angle and feed speed. These three main parameters have to be considered for dry ice blasting cleaning devices.

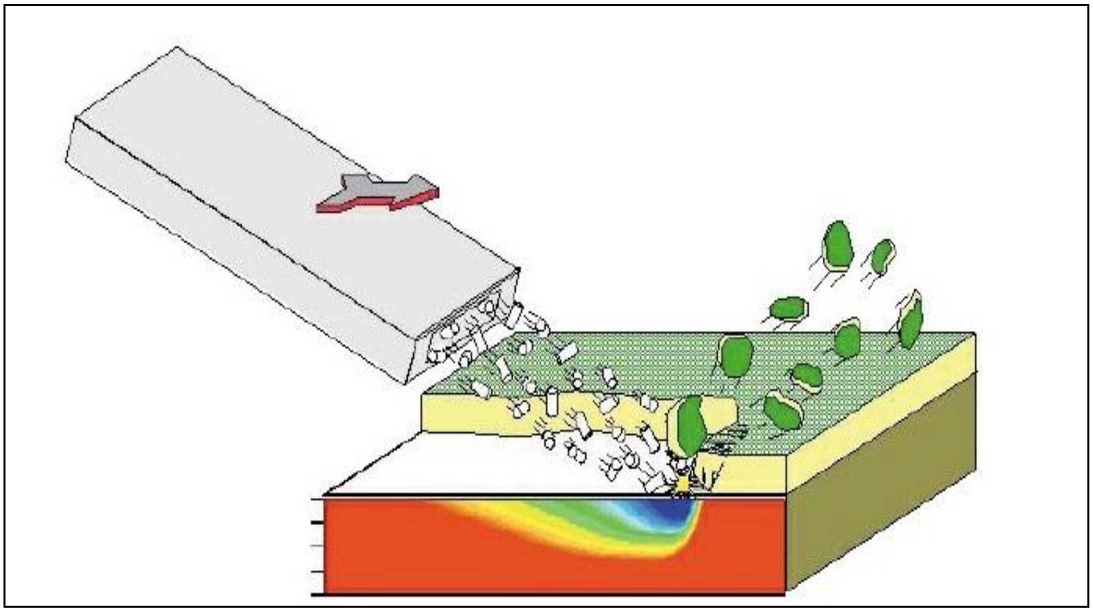


Figure 8 - Dry Ice Blasting [20]

Sponge blasting Method: Sponge blasting is another alternative method of dry blasting. Small pieces of sponge are used as abrasive materials blasted at the surface to be cleaned. The sponge flattens against the surface, exposing the abrasives and then capturing the contaminants within the sponge. The sponge is then regenerated to be used again. This system creates low waste materials from surface and dust. With such low emissions, it is better for worker health and safety, and also for the environment. Low pollution and waste generation are the main factors for system selection. The sponge has a fairly soft structure for the blasting cleaning process; therefore, the system is highly suitable for every type of cleaning surface. Media softness may require that the system is used with higher pressure range between 80 to 240psi. This is higher than most of the dry cleaning processes [18]. The sponge blasting method has a couple big disadvantages from the other types of the dry blasting cleaning methods. First, the cost of the equipment and sponge media are high. Second, the system needs another step of cleaning after this step because of the small dust particles that can stick on cleaned surfaces and holes. Water pressure, water bathing or vibratory cleaning can be a good fit for the system as a second step. This also makes the system more expensive. The last disadvantage of system is that sponge blasting is quite a new system and needs trained personnel. These three disadvantages make the system more expensive than the rest of the dry blasting systems but the system's cleaning and environmental results make it more desirable than others.

Wet Blasting: Wet blasting is spraying air and slurry mixes with high velocity onto a workpiece. The slurry consists of treated water, chemical solvents and different types of media for different types of material and contaminants. The system has to be set up to keep the slurry mixture density stable for cleaning quality and uniform on the surface, because wet abrasive blasting pressure is higher than with dry abrasive blasting. The use of water and chemical in combination with abrasives significantly reduces the amount of dust. In industrial activities, two main types of wet blasting are in use. The hydroblast technology system uses compressed water in a range between 5000 to 10000 psi [15]. The compressed water transports a continuous stream of slurry cleaner to workpiece. This system generally requires suitable chemicals to clean parts effectively. The vaporblast technology system accelerates a slurry mixture through the nozzle by a medium (10000-30000 PSI) pressure water jet [12]. The system impacts all the contamination layers with a very high velocity. Most wet blast equipment is an automatic close cabinet system for using high velocities. The experimental results show blasting material, slurry mixture, pressure angle, pressure of the blast stream, and the air flow rate would have a direct impact on the effectiveness of the system [14]. The pH and water soluble content are extremely important in determining if an abrasive blasting media is suitable for wet abrasive blasting. The pH of the abrasive is generally between 5.7 to 10.1, therefore the system requires a rinse or water wash step after the cleaning process. This step will stabilize the pH level [12].

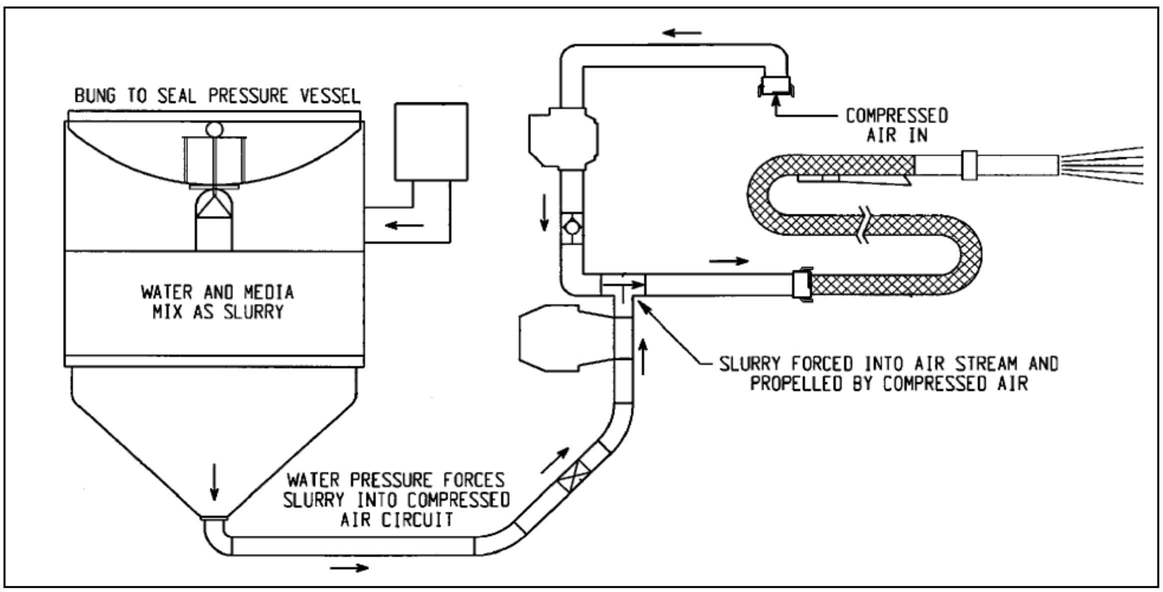


Figure 9 - Wet Abrasive Blasting System [12]

In industrial activities several variations of wet abrasive methods are used. Two types of processes are accepted as the main alternatives:

Hydroblast Process: Water pressure mixes sand with water and chemicals.

Vaporblast Process: The abrasive is suspended in a liquid and projected at high velocity by a jet of compressed air.

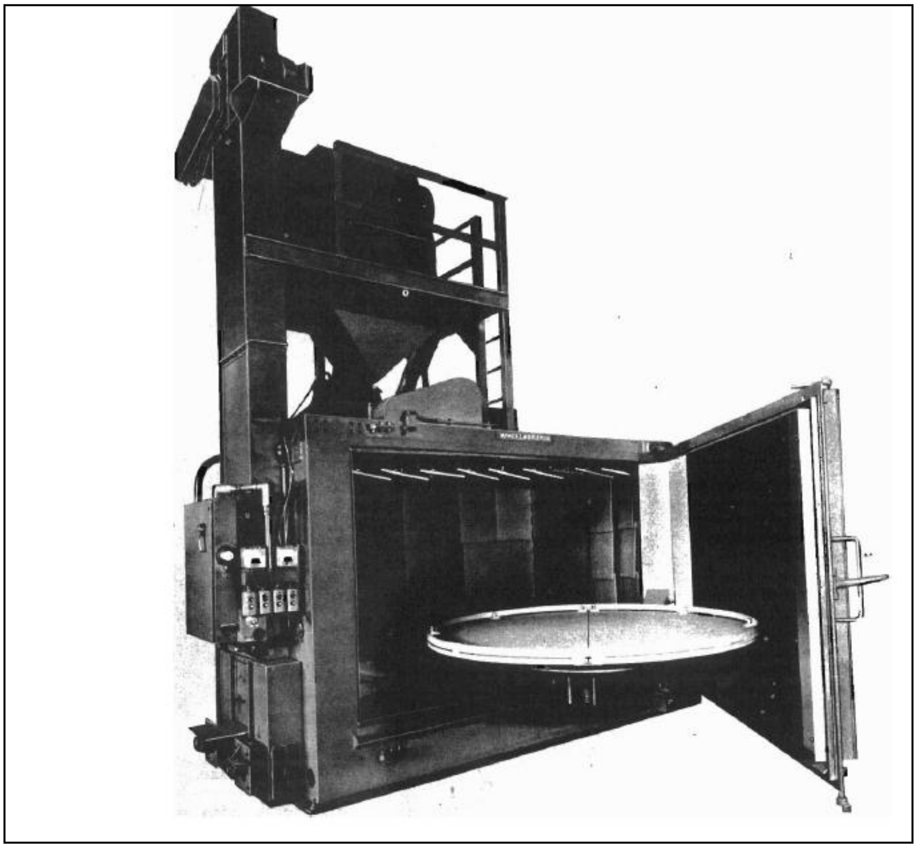


Figure 10 - Automatic Swing Table Blast Cleaning System [16]

Dry and Wet Abrasive Blasting: Dry abrasive blasting and wet abrasive blasting cleaning processes can be suitable for rust, carbon, oxidation, oil, grease and dirt but wet abrasive blasting is also good with other types of strong contaminants [10]. If the processed material type is soft, wet abrasive blasting method is the better option. When media is mixed with water and other types of chemicals, slurry damages the surface less than dry media shown in figure 11.

Type and size of the media is another important parameter for the cleaning process as shown in figure 11. Small media is less harmful than large media and wet abrasive cleaning is less harmful than dry abrasive blasting. These types of micro damages, which are shown in the figure, are really important for small parts. If they harmed, they might not be usable for remanufacturing. During system selection, part size is another important parameter to consider [17].

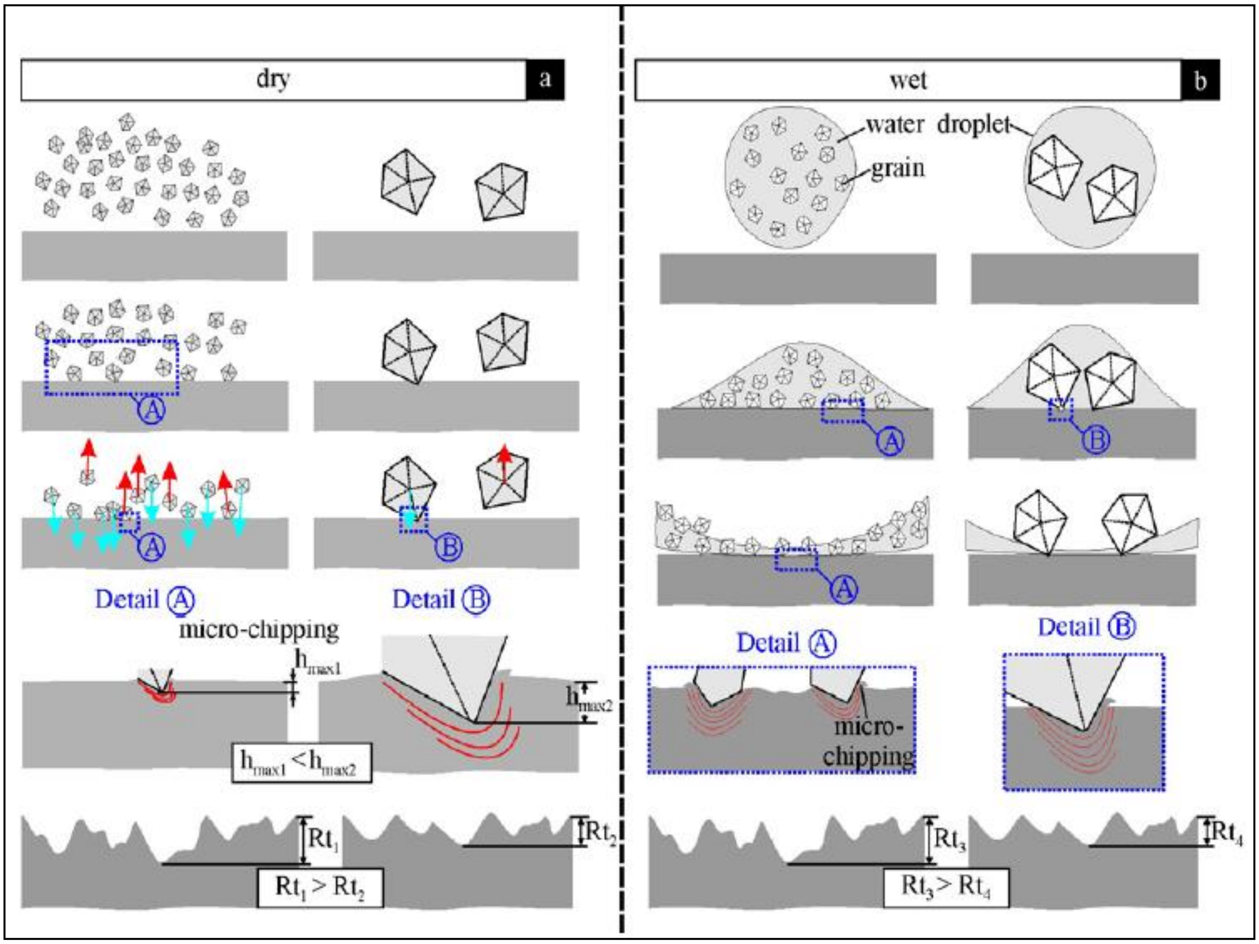


Figure 11 - Dry Blasting vs. Wet Blasting [17]

In dry abrasive blasting manual systems, parts are generally cleaned by hand in a cabinet. Abrasive media is compressed by air or water pressure through a nozzle that is controlled by the operator. The operator has to be trained well, because system is sensitive and uses high pressure. Any type of small mistake can have considerable consequences; that part can be damaged or the system can break down. The system has generally used the media saver storage reservoir for reuse. After the storage, the second step for re-use is a separation system where contaminants can be transported to another box for separation with air. Reusable media is returned for reuse the next time. In an automated system, the operator manages the process outside of the cabinet. If the system is portable, generally the media is lost. Therefore, an automatic system is environmentally advantageous and less expensive. In an automatic system, parts are loaded into a basket or onto a belt, and the blasting process begins. Mechanical blast systems are generally more powerful than air blast systems, but many parts do not require this additional power to be cleaned effectively. The key to getting the best results is choosing the right blast equipment and media for the substrate and contaminants to be cleaned. Wet abrasive blasting systems work quite similarly to dry abrasive blasting systems. The main difference is that the chemical and water cannot be used again, but media can separated from the waste and sent back to system. Wet abrasive blasting has lower pollution and dust than dry abrasive blasting, but the cleaning cost is greater [14]. If we combine dry and wet abrasive blasting and appraise together;

Advantages

- Excellent means of removing rust, ash, paint, burned-on carbon, scale, and oxidation
- Produces a uniform surface finish
- Able to clean a wide range of substrates by altering pressure and media
- When deciding between wet and dry abrasive blasting and media type, system can be suitable for every type of surfaces

Disadvantages

- Well trained workers are required.
- Labor costs may be prohibitive for manual systems with high throughput.
- Residual blast media may damage the part.

- Dry blasting has high dust emission and wet abrasive has high chemical waste.
- Media Type and Specification

Media type is one of the main parameters for choosing a cleaning process. Each media type is suited for different types of contamination and surface types. The figure represents the specification of different types of media.

Abrasive	Composition	Mohs Hardness	Density (gms./cu. cm)	Dusting	Recycling
Silica Sand					
Best Quality	Crystalline Silica	7.0	1.6	Low	No
Average Quality	Same	6.5	1.6	High	No
Staurolite/Zircon	Iron Aluminium Silicate	7.5	2.0	Mod	No
Garnet					
Almandite	Iron Aluminium Silicate	7.5	2.0	Low	Yes
Andradite	Calcium Silicate	6.5	1.8	High	No
Olivine	Iron Silicate	6.5	1.9	High	No
Spec. Hematite	Iron Oxide	6.0	2.3	Mod	Yes
Copper Slag	Iron Silicate Glass	6.0	1.6	Mod	No
Nickel Slag	Nickel Iron Glass	6.0	1.6	High	No
Iron Slag	Iron Silicate Glass	6.0	1.6	High	No
Coal Boiler Slag	Ca, Iron Silicate Glass	6.0	1.4	High	No
Steel Grit/Shot	Iron (Steel)	6.0	2.2+	Low	Yes
Baking Soda	Sodium Carbonates	2.0-3.0	1.1	High/Low*	No
Crushed Glass	Alkaline Silicate Glass	6.0	1.6	High	No#
Organic Media	Various	2-3	0.6-1.0	N/A	No

Table 4 - Summary of Abrasive Characteristics [21]

Description	Glass beads (a)	Coarse Mineral Abrasives (b)	Fine Angular Mineral Abrasives (c)	Organic Soft Grit Abrasives (d)	Plastics Abrasives (e)
Physical Properties					
Shape	Spherical	Granular	Angular	Irregular	Cylindrical (diameter/length = 1)
Colour	Clear	Tan	Brown/white	Brown/tan	Nylon: white, polycarbonate: orange
Specific gravity	2.45 – 2.50	2.4 – 2.7	2.4 – 4.0	1.3 – 1.4	Nylon: 1.15 – 1.17, polycarbonate: 1.2 - 1.65
Free silica content	None	100%	<1%	None	None
Free iron content	<1%	<1%	<1%	None	None
Hardness (MOH)	5.5	7.5	9.0	1.0	R-110 to R120
Media Comparisons					
Toxicity	None	High	Low	Low/None	None
Metal Removal	Low/None	High	High	None	Deburring Only
Cleaning Speed	Medium/High	High	High	Low	Low
Peening Ability	High	None	None	None	None
Finish Achieved	Range (various matte)	Rough anchor	Various matte	Smooth	Smooth
Surface Contamination	None	Medium	Medium	Medium/High	Low to None
Suitability for Wet Blasting	High	Low	Low	Low	Low
Suitability for Dry Blasting	High	High	High	High	High
Standard Size Ranges	20-325	8-200	80-235	60-325	0.76 by 0.76 mm (0.030 by 0.030 in.)
	U.S. mesh	U.S. mesh	U.S. mesh	U.S. mesh	1.1 by 1.1 mm (0.045 by 0.045 in)
					1.5 by 1.5 mm (0.060 by 0.060 in)
Consumption Rate	Low	High	Medium	High	Very low
Cost Comparison	Medium	Low	High/Medium	High/Medium	High/Medium

Table 5 - Physical Properties and Comparative Characteristics of Nonmetallic Abrasives [21]

Glass beads are used for cleaning, finishing, light-to-medium peening and deburring. Coarse mineral abrasives such as sand are used where metal removal and surface contamination are not considered. Fine angular mineral abrasives such as aluminum oxide are used in cleaning when smooth finish and surface contamination are not important. Organic soft grit abrasives, for example, walnut shells, are used in light deburring and cleaning of fragile items. Plastic abrasives such as nylon and polycarbonate are used to deflash thermoset plastic parts and deburr finished machine parts.

Emission, Environmental Health and Safety: Dust, chemical waste and noise are the main effects of blasting operations. Filters and bag houses are the most important protection parts for dust control with a dry blasting system. If the controller cleans the bag system, it does not need major maintenance. The controller needs to use a mask to minimize the risk when he/she changes the bag and uses the system. The bag and cabinet can have every type of dust and also small amounts of media (zinc, plastic, walnut shell, corncob, paint dust etc.). The controller or operator also has to be careful about the noise levels. If noise levels are higher than the safety level, the operator has to use earplugs [10]. Wet abrasive blasting uses aggressive chemicals with ultrasonic cleaning. These chemicals are either strongly acidic or strongly basic, and have their own health risks. There are many very good neutral pH or near neutral pH chemicals that do an excellent job of cleaning greasy and dirty parts [14]. Wet abrasive cleaning systems have less dust issue than dry abrasive blasting systems. The purchasing and research and development departments have to do enough investigation before purchasing the safety equipment. Contaminants removed from the parts may result in the creation of hazardous waste materials. Dust and chemical wastes have to be characterized and identified, especially when it comes from chemical reactions. Therefore, contaminant character has to be found before using that system [13].

Cost: The cost of air driven manual blasting equipment can be between $800 for a small unit to $14,000 for a floor unit. Another part of the system is the shot basket blasting system and it costs between $7,000 to $14,000 or more, depending on capacity and other specifications of system. If you prefer an automated system, a robotics-controlled batch system costs extra depending on features and size. These systems are considered portable systems.

There is a wide variety of blasting cleaning equipment available to the remanufacturers. The least expensive units are simple bench top cleaning systems. These systems include both manual and automatic systems and different sizes of cabinets, pressure machines, and safety features. More elaborate cleaning systems with more equipment are also available at a cost of $15,000 to $55,000 for dry abrasive blasting system [10]. For wet abrasive blasting system cost is $17,000 to $95,000. Energy consumption is approximately 1.14kw/kg blast and 1.52kw/kg blast, which is acceptable with great cleaning result [12].

Performance

Abrasive blasting systems, both wet and dry, have been used with success and proven in experiments. Direct pressure, induction-siphon and induction-gravity methods are quite effective on different contamination types. Dry-ice and sponge cleaning methods are new and significantly better than other dry cleaning methods but they still need to be improved. Also, system and worker costs are much higher than other types of cleaning methods. This study separated wet abrasive blasting into two different groups, hydroblast and vaporblast processes, based on air pressure and water pressure. Wet and dry blasting cleaning methods need correct information for good setting on cleaning processes to meet clearance levels not to be endangered [10] [14].

2.1.2 Laser Cleaning

One of the most widely distributed cleaning processes in industry is laser cleaning. Laser cleaning shows very effective performance and has the most suitable features. Laser cleaning is the most effective method of removal of soiling particles of different materials and sizes, and films and coatings from solid surfaces. This study mainly covers the cleaning of dirt, grease, rust, sand, graphite, facecoat, paint, oils, soils, carbon, inorganic materials, and organic contaminants with laser cleaning processes [22][23][24]. Laser cleaning is nonchemical and inexpensive. It can be used for the removal of various types of contamination, including those that cannot be cleaned by the traditional cleaning methods. The main advantage of using lasers for cleaning metallic surfaces is that the removal is well controlled and carried out layer by layer. Therefore the system can be designed for cleaning only the undesired contamination layer. This key difference makes laser cleaning results better than other traditional cleaning methods [22].

System of Process: Laser cleaning effectively cleans every type of surface and contaminant, but this study will only handle the laser cleaning on metal surfaces. Two types of cleaning methods are used for surface cleaning: dry cleaning and steam laser cleaning. The technique of dry cleaning is simple, but it is less effective than for steam cleaning and the required laser intensity is higher. Power thresholds of steam cleaning are two or three times higher than for dry cleaning. Sometimes dry laser cleaning can result in local damage of the surface [25]. These two laser cleaning methods are also designed for two different laser types: TEA CO_2 and Nd: YAG laser cleaning. Lasers offer many advantages over traditional methods. Laser cleaning is a selective, non-contact method that leads to better preservation of the surface and surface details. Furthermore, laser cleaning is safer both for the workplace and for the larger environment. Laser cleaning is successful with both organic and inorganic contaminants. The main laser wavelength for TEA CO2 lasers is 10,600 nm. For Nd:YAG lasers, 1064 nm, 532 nm and 266 nm(UV) have been used for different types of materials and contaminants. To determine the most suitable wavelength for successful cleaning, careful evaluation by microscopy has to be carried out. After laser type and wavelength have been selected, the next important setting for laser cleaning is threshold of fluency which will depend on the absorption mechanism, particular material properties, microstructure, morphology, the presence of defects, and laser parameters such as wavelength and pulse duration. Typical threshold fluencies for metals are between 1 and 10 J/cm^2, for inorganic insulators between 0.5 and 2 J/cm^2, and for organic materials between 0.1 and 1 J/cm^2 [26].

Dry Cleaning: In dry laser cleaning, particles can be ejected from particulate-contaminated surfaces by short-pulse laser irradiation. The proposed mechanism of the ejection is fast thermal expansion of the particle and/or solid surfaces, which induces a large cleaning force to overcome the adhesion force between particles and solid surfaces [27]. Dry laser cleaning is generally based on a rapid thermal energy transfer between the laser beam and the surface. The resulting rapid thermal expansion of the components provides the force to eject particles. TEA CO2 and Nd: YAG types of laser beams are both used with dry cleaning.

Steam Cleaning: In steam laser cleaning, the proposed mechanism is assumed to be the momentum transfer from the laser-heated and suddenly evaporating liquid film to the particles on the solid surfaces [27]. Application of a thin water film on the surface before the laser beam is used to increase the cleaning effect and is especially helpful if the crust is difficult to remove. Thin water or liquid film sprays the surface from the heater part of the system and the other side of heather receives the gas which is needed to clean contamination. TEA CO2 and Nd: YAG types of laser beams are also used with steam cleaning.

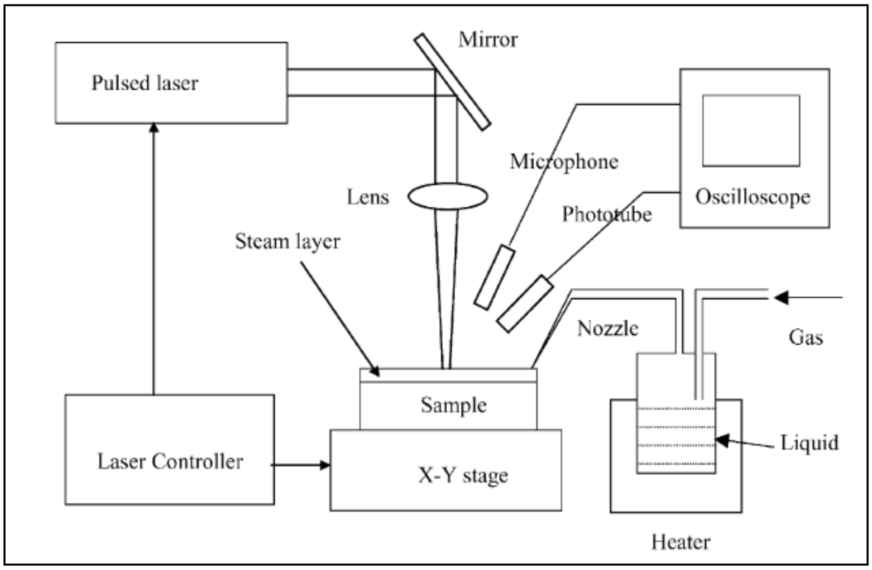


Figure 12 - Steam Cleaning [28]

Dry and Steam laser cleaning methods are also designed under two different laser type; TEA CO_2 and Nd: YAG lasers cleaning.

TEA CO2 laser: The TEA CO2 laser is used at a wavelength of 10,600 nm in the form of short pulses, with an energy of 2–4 J with a typical duration of 100–1000 ns at a repetition rate of up to 20 Hz. [29]. As can be seen in Figure-13, at λ = 10,600 nm, most metals absorb poorly; however, organic materials show a strong absorption at this wavelength. For this reason, the TEA CO2 laser is most suitable for cleaning metal artifacts. Absorption of radiation in organic compounds is due to the interaction of photons with different radicals.

Nd:YAG laser, IR and green: The Nd:YAG laser emits short duration, ≈ 10 ns, pulses with an energy of 0.5 J in the infrared, 1064 nm, and 0.25 J at the second harmonic (green), and at 532 nm wavelength. A pulse repetition rate of up to 10 Hz is possible with this equipment [29]. The optimum energy density values were in the range of 0.4–2 J cm^2, depending upon the wavelength used [29]. As can be seen in figure-13, at λ = 1064 most metals absorb poorly but organic materials show a strong absorption at this wavelength. The TEA CO2 laser is less effective than the Nd:YAG laser in removing oxide layers [22].

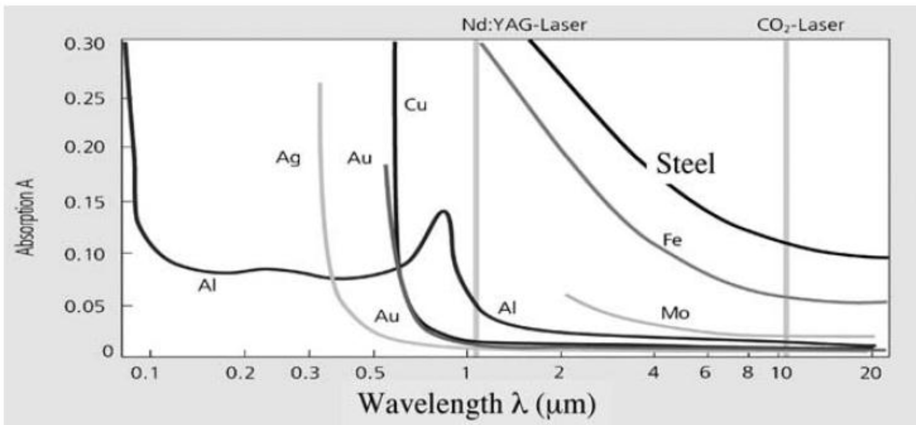


Figure 13 - Absorption characteristics of different metals as a function of wavelength [29]

Cleaning by laser beam directed on the angle to the surface: Laser cleaning is designed to direct a laser beam to the surface with a normal beam line. The results of experiments show that the quality of laser cleaning improves with the different laser beam angle to the surface.

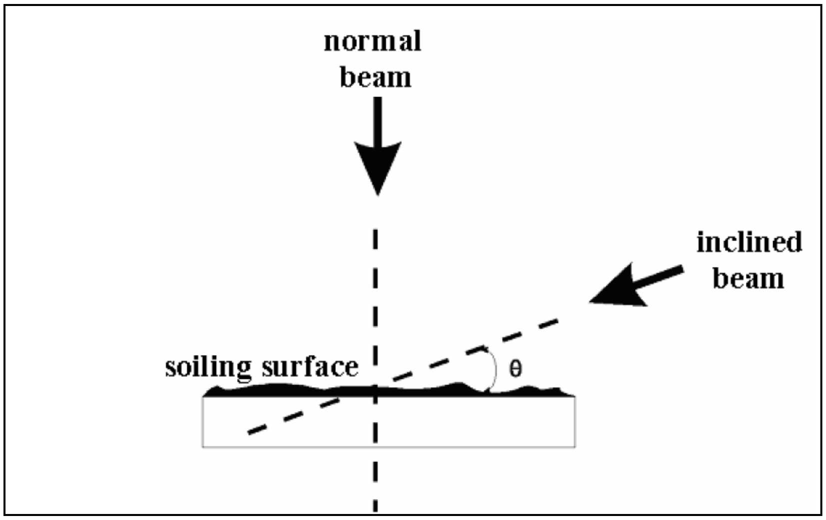


Figure 14 - The scheme of laser cleaning on the angle to surface [55]

If the laser beam isn't used with a normal beam, thermo elastic stress causes laser radiation near or under adhered particles of dirt. This radiation is significantly more than normal incidence of the laser beam. With an inclined beam, contamination particles of dirt can be treated easily from the surface. Therefore, an inclined laser beam increases the area of the treated zone and the effectiveness of the laser treatment. Also, with correct settings and power it is more effective than normal beam. "By irradiation of the surface by beam directed under the angle of 20° the square of treated zone is in 10 times larger than in case of treatment by normally directed beam." [25].

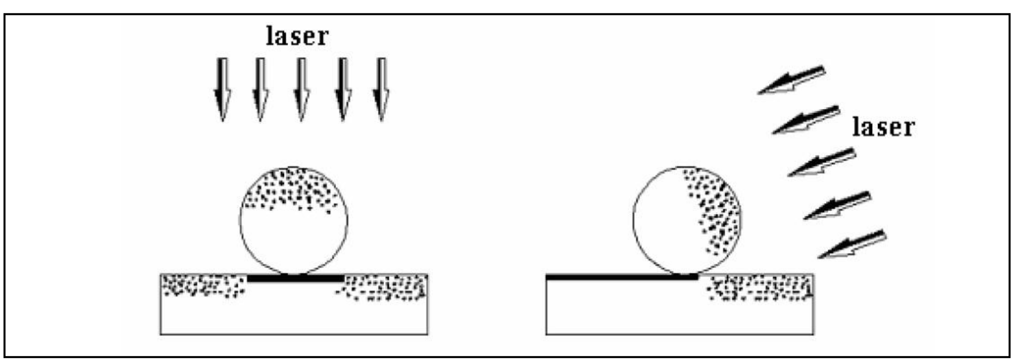


Figure 15 - Position of irradiated and shaded zones by normal (a) and inclined (b) laser incidence [25]

Use of an inclined laser beam helps to solve one other problem as well. Qualitative analysis of Nd:YAG laser beam of normal and inclined incidence shows the adsorbing film after laser cleaning of contaminated surface. After collecting this information and research, it was shown that an inclined beam had a higher concentration of deposited products than in the case of treatment by normally directed beam [25].

Advantages

- System can clean the parts without damage with correct wave length.
- System has high cleaning efficiency with flat surface.
- System able to clean sensitive parts layer by layer.
- System has low emission results.

Disadvantages

- Batch size is smaller than other types of cleaning processes.
- Energy consumption is high
- System cost is considerably high.
- System needs well trained operators.
- Emission and Environment, Health and Safety

The laser process is well suited to most surfaces with high efficiency. This system is one of the most environmentally friendly of the traditional cleaning methods. Laser cleaning is also safer for workers because the system works automatically. Workers using this system have to be well trained because small mistakes cause big consequences in this system. One disadvantage of the system is that it uses ultraviolet and radioactive beams, and the worker has to be careful during the process. The noise level can also be dangerous. If laser beams contact the person’s body parts, it can cause great harm to the worker. The system's biggest advantage is that contamination can be cleaned layer by layer. This advantage of the system helps when taking the cleaned contaminant out of the cabinet system. After each layer, cleaning dirt can be cleaned from the system and processes differently. Laser cleaning is effective on organic and inorganic cleaning, but organic and inorganic cleaned contaminants cannot be in the same process after being taken out from the system. Gas and dust level could be considered low [22]. There are correct settings for each type of material that do an excellent job of cleaning organic and inorganic contaminants from parts.

Cost: There is a wide variety of laser cleaning equipment available to the engine parts rebuilder. The least expensive units are simple bench top cleaning systems. Dry laser cleaning system prices range from $65,000 to $430,000. Steam laser cleaning systems with more equipment are also available at a cost of $145,000 to $430,000 [24]. Energy consumption is approximately 2-12kw per cycle, with great cleaning result [24]. Energy consumption is much higher than most of the traditional cleaning processes but emission and environmental impact and cleaning result is less.

Performance: For the most suitable model, angle, laser type, wavelength, density and type of cleaning (dry or steam) have to be taken into consideration as system settings. With optimum settings, cleaning results are quite satisfactory. Systems are designed to clean mainly dirt, grease, rust, sand, graphite, facecoat, paint, oils, soils, carbon, inorganic materials, and organic contaminants [22][23]. The technique of dry Laser cleaning is simple, but its effectiveness is less than steam laser cleaning [30]. Power thresholds of steam cleaning are two or three times higher than for dry cleaning [25]. Typical threshold fluencies for metals are between 1 and 10 J/cm^2, for inorganic insulators between 0.5 and 2 J/cm^2, and for organic materials between 0.1 and 1 J/cm^2[26]. The main laser wavelengths are 10,600 nm for the TEA CO2 laser. For Nd:YAG lasers, 1064 nm, 532 nm and 266 nm(UV) have been used for different types of material and contaminants. As mentioned above, the figure shows the suitable wavelength for each material. Also laser type comparison is shown on the bottom. The literature review shows that across the different settings, laser cleaning is one of the most efficient and effective cleaning process. Laser type comparison explained below,

1. An Nd:YAG laser is a more effective cleaning tool than a TEA CO2 laser for corroded steel.

2. Wet corroded steel surfaces can be cleaned more effectively than dry surfaces.

3. TEA CO2 lasers are more effective at cleaning polymeric materials off metal surfaces than Nd:YAG Lasers.

4. Frequency quadrupled (ultraviolet) Nd:YAG laser light is an effective cleaning tool for silver threads which are combined with silk threads. The other three wavelengths noted above damage both the silver and the silk.

5. Frequency doubled (Green) Nd:YAG Laser light cannot be used to clean copper oxides from copper substrates without some surface melting of the copper or the copper oxide. This laser-material interaction is, therefore, inappropriate for conservation purposes [22].

2.1.3 Ultrasonic Cleaning

One of the most popular cleaning processes is ultrasonic cleaning. Ultrasonic cleaning shows very effective performance with the most suitable features. Ultrasonic cleaning design is based on an aqueous tank system, which uses ultrasonic energy to remove rust, oxidation, dirt, grease, oil, and carbon from parts [31]. Heavy layers of contamination can also be removed by ultrasonic cleaning but require more aggressive chemicals. Ultrasonic cleaning is one of the most effective cleaning in traditional cleaning methods. One disadvantage in the use of ultrasonic energy is system set up is really sensitive if it doesn’t set correctly system can damage to parts. Therefore there must be consideration in selection of frequency and power in the cleaning tank, contamination and material type has to be considered. Influence design of the equipment and design of the process. System has different parameters to set it up correctly for different contamination type. Frequency, chemical and transducer types are main parameters on ultrasonic cleaning process. Heavy or light layers of contaminants can be removed by ultrasonic cleaning but require more aggressive chemicals and/or with different frequency. Ultrasonic cleaning systems are composed of ultrasonic transducers mounted on a radiating diaphragm, an electrical generator, and a tank filled with cleaning chemicals as shown on the figure. Therefore ultrasonic cleaning processes are separated into two different groups based on transducer type. There are two types of ultrasonic transducers used in the industry: piezoelectric and magnetostrictive.

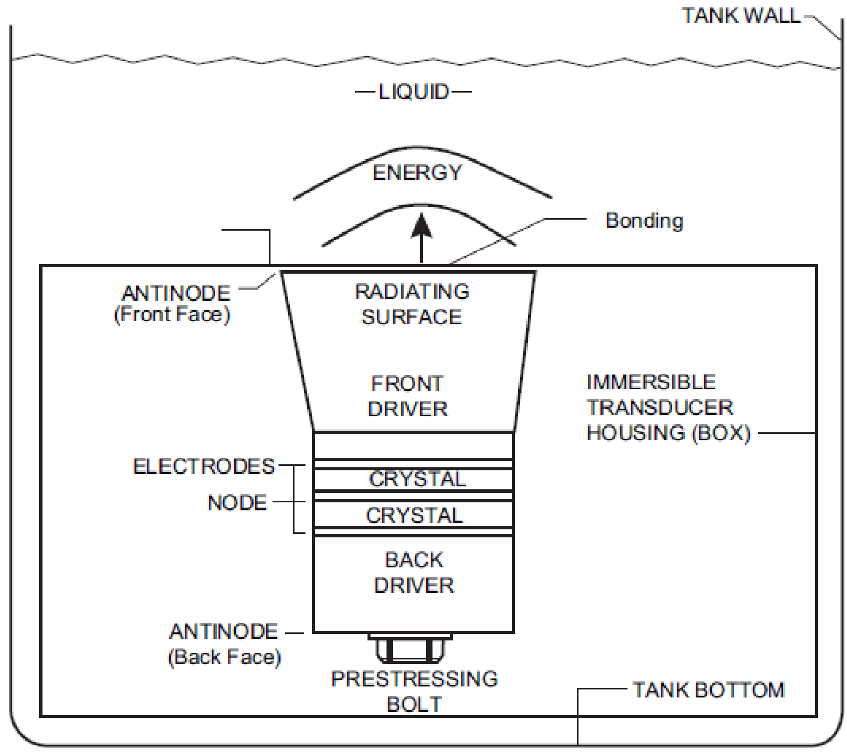


Figure 16 - Ultrasonic Cleaning Tank System [32]

Magnetostrictive Transducers: Magnetostrictive transducers use magnetostriction in certain materials expands and contract when placed in an alternating magnetic field. Alternating electrical energy from the ultrasonic generator is first converted into an alternating magnetic field through the use of a coil. The alternating magnetic field is used to inspire the mechanical vibrations at the ultrasonic frequency of nickel, steel, copper, rubber, iron and other ferromagnetic material, which are used in the surface to be vibrated. Because of magnetostrictive materials are identical to a magnetic field, the frequency of the electrical energy applied to the transducer is half that of the desired output frequency. This is due primarily to the fact that the magnetostrictive transducer requires a dual energy conversion from electrical to magnetic and then from magnetic to mechanical [32][33].

Piezoelectric Transducers: Piezoelectric transducers convert alternating electrical energy directly to mechanical energy through the use of the piezoelectric effect. Electrical energy at the ultrasonic frequency is set the transducer. This electrical energy is transferred to piezoelectric element in the transducer. These vibrations are directed into the liquid through the contaminant. Transducers incorporate stronger, more efficient, and highly stable ceramic piezoelectric materials. The vast majority of transducers used for ultrasonic cleaning utilize the piezoelectric effect.

The transducers, which give the vibration at the high frequency electronic generator source, cause amplified vibration of the diaphragm. This amplified vibration is the main source of positive and negative pressure waves in a cleaning tank. When waves are transmitted in water, these pressure waves create the cavitations process.

Cavitation is a process where the constructive interference of sonic energy causes the formation of significant bubbles in the cleaning liquid. When these microscopic bubbles implode they produce microscopic jets of liquid that can impinge on the surface of parts to be cleaned. These high velocity jets remove particles from surfaces and convey cleaning chemicals to organic and inorganic chemical contamination on the surface.

The wave frequency of the transducer determines the size of the bubbles. Lower frequency produces larger bubbles with more energy. The more powerful the cavitations process is the larger the imploding bubbles. The higher the frequency, the less aggressive the cavitations are and the smaller the implosions [32][33].

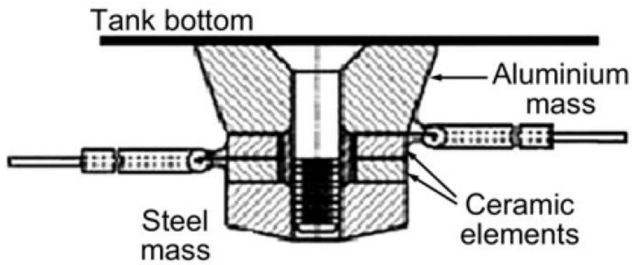


Figure 17 - Piezoelectric Transducer [32]

System of Process: Ultrasonic cleaning uses high frequency sound waves in the range between 15 to 400 kHz to remove a variety of contaminants from parts immersed in aqueous media. Ultrasonic cleaning works by producing sound waves in liquids. The waves consist of both high and low pressure fronts. The expanding and collapsing bubbles loosen contaminants on the part surface and the chemical cleaners dissolve the free contaminants. When chemicals are used, the system's pH generally stays in a range between 4.5 to 6.8. System temperatures remain in the range between 70F to 180F and thus, improve the efficiency of system. Typical industrial systems' frequency sound wave is in the range between 40 KHz to 200 KHz, which can handle the particle sizes in the range of normal cleaning. Ultrasonic cleaning systems are efficient between 15 KHz to 25 KHz but higher frequencies are used in the computer industry where tiny particles need to be removed [32][34]. Different frequency choices are available for cleaning and they are shown below:

- 15 – 40 kHz – heavy-duty cleaning for items such as engine blocks and heavy metal parts, and for removal of heavy greasy soils.
- 40 – 70 kHz – general cleaning of machine parts, optics, and other components. This frequency range is very good at removing small particles.

- 70 – 190 kHz – gentle cleaning of optics, disk drive components, and other sensitive parts.
- 190–400 kHz – ultrafine cleaning of semiconductor wafers, ultrathin ceramics, optics, and highly polished metallic mirrors or reflectors [34].

Pressure in the liquid could generate the cavitation bubbles and it would grow rapidly.

When they leaved the negative pressure region, the pressure behind made the cavitation bubbles close and it produced a strong shock wave and local high temperature and high pressure. It is shown on the model diagram of cavitation. The action of the cavitation is shown in the other block diagram. This represents difference between bubbles collapse and vibration effects difference [33].

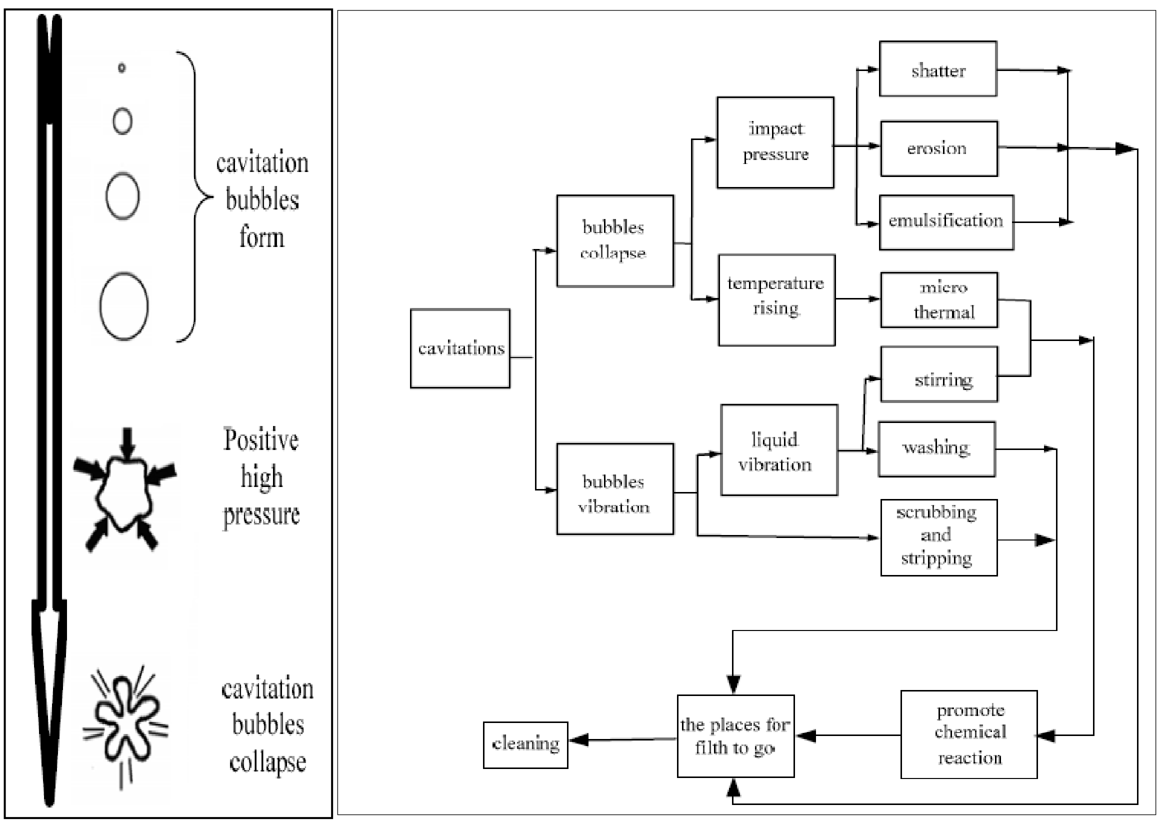


Figure 18 - The model diagram of "cavitations" and the functional block diagram of the ultrasonic cleaning [33]

Stage changes diagram shows, diagrammatically a solvent degreasing process to which in ultrasonic cleaning process. The solvent degreaser may be operated by utilizing one of the popular solvent degreasing cycles. The gross soil is removed during this regular cycle of the cleaning process and ultrasonic chamber. The work piece is always immersed in the liquid in the ultrasonic chamber. The temperature of the solvent in the ultrasonic system keeps at approximately 140°F which seems to be optimum for cleaning [35].

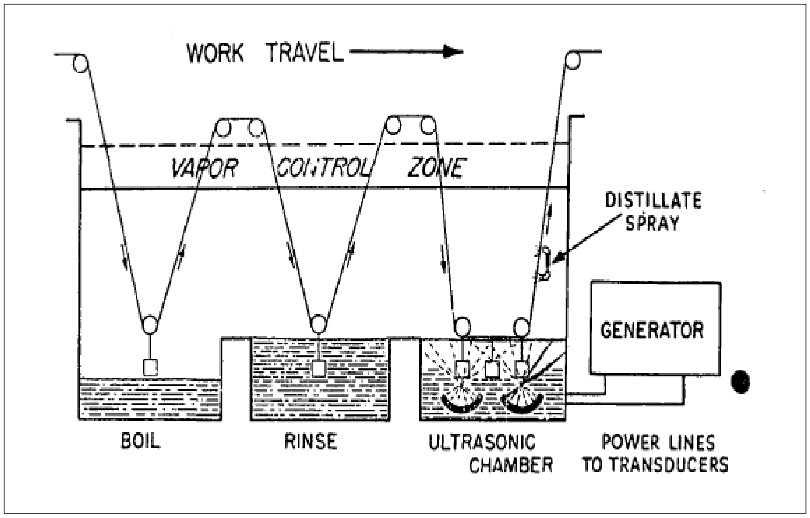


Figure 19 - Stage Changes of Ultrasonic Cleaning [35]

After chemical mixed solvents (detergents) are used, a water rinse step has to be next in order to stabilize the pH level. In the mean time, a water rinse can help to clean the decontaminated dirt from the surface. If hot water is necessary to use to clean oil and grease from the surface, a water heater can be integrated into system to increase the system efficiency.

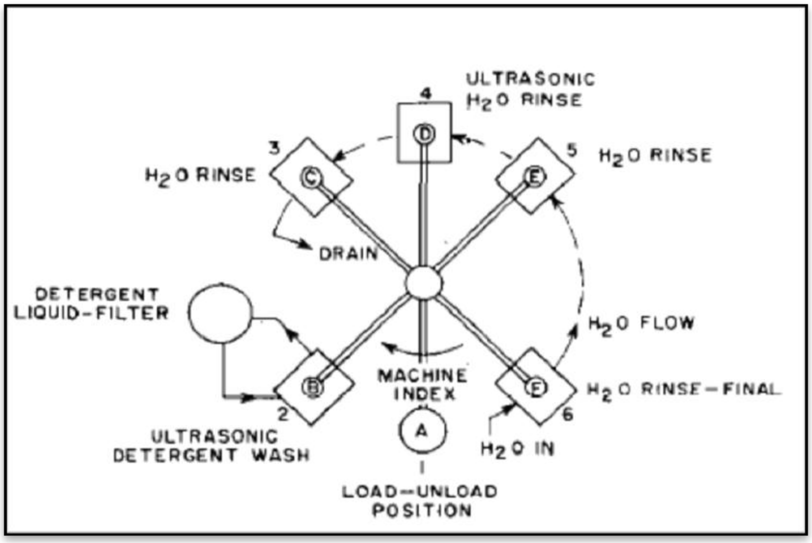


Figure 20 - Ultrasonic cleaning Schema [36]

Advantages

- System can clean the parts without damage with correct frequency and chemicals settings.
- System has high cleaning efficiency with small apertures, blind holes, and crevices.
- System able to clean sensitive parts with relatively mild chemicals.
- System has low emission results.

Disadvantages

- Large loads are not cleaned as quickly as small loads due to energy absorption.
- Extremely thick layers of grease, and grease mixed with dirt, are slow to be removed.
- Generally, a rinse and drying step is required with aqueous cleaning to remove chemical residues.
- With the lower frequency the noise levels increase to a hazardous level.

Emission and Environment, Health and Safety: The ultrasonic process is well suited to aqueous cleaners. As such, it provides an environmentally friendly alternative to mineral spirit cleaners. Aqueous cleaners are also safer for workers because they eliminate the use of flammable solvents and the health risks associated with hydrocarbons [38]. Some of the more aggressive aqueous chemicals used in ultrasonic cleaning equipment are either strongly acidic or strongly basic, which have their own health risks. There are many very good neutral pH or near neutral pH chemicals that do an excellent job of cleaning greasy and dirty parts. One disadvantage with the lower frequency is that the noise levels increase at these frequencies. Ear protection or acoustic insulation is generally required for these tanks [31].

Cost: There is a wide variety of ultrasonic cleaning equipment available to the engine parts rebuilder. The least expensive cleaning systems are about the size of tank, with price ranges from $2,000 to $7,500. More elaborate cleaning systems with more equipment are also available at a cost of $10,000 to $180,000. For efficiently cleaning, second range is more accurate for factories. Systems are with price ranges from $2,000 to $7,500 for more school or research facilities. Energy consumption is approximately 0.86kw per cycle, which is quite low with great cleaning result [31][37].

Performance: For the most suitable model, concentration, cycle time, temperature, and ultrasound waves have to take in to consideration for system settings. With optimum settings cleaning results are quiet fulfilling. Systems are designed to clean mainly paint, oil, carbon, grease, rust and oxidation from surfaces. The main types of transducers are piezoelectric and magnetostrictive transducers. Magnetostrictive transducers use metals that expand and contract in an alternating magnetic field; nickel alloys, iron, steel, refractory metals are the most common material. Piezoelectric transducers generally used for steel, aluminum, plastic, ceramics, copper, rubber, Iron and refractory metal. Piezoelectric transducers are relatively cheaper then magnetostrictive transducers but not stronger. According to this information system works very well with metal surfaces and other types of materials.

2.1.4 Vibratory Cleaning

Vibratory finishing and cleaning is a widely used industrial process that modifies the properties of metal, ceramic, and plastic parts. It is used to polish metal and plastic components, to smooth the sharp edges of steel parts cast to harden and texture metals, and to clean surfaces by removing rust and other contaminants [39]. A few of the many applications where vibratory finishing has been successfully applied are the polishing of coins, gears, plastic eyeglass frames, and golf balls; smoothing of sharp edges on steel parts that have been stamped or cast for the automotive industry; and the texturing and hardening of surfaces [40]. Cleaning systems are generally used on low levels of rust, paint, dirt, gaskets, carbon, oils and greases on metal surfaces. Vibratory cleaning is not effective enough for strong contaminants; therefore it is the second step of cleaning processes [41].

System of Process: Generally speaking, a vibratory finisher is a container filled with media that uses a device to apply time variable forces to the container to develop a periodic motion. Selected media generally ranges between ceramic, resin-bonded, steel, aluminum, aluminum oxide, and silicon carbide abrasive types. The size of the media is between 5-7mm ranges [42][40]. The difference in media types consists of hardness, shape, and density. Soft media works better with soft material and does not harm the surface during the process. Soft materials are not as effective as stronger media types. Shape and size are also dependent on contamination type. Small size media types are good for sensitive cleaning.

The frequency of the vibratory cleaning machine is the most important parameter for the system. The frequency of rotation is usually in the range of 40 ± 20 Hz. The media type and frequency are chosen to suit a specific surface finishing application. Typical contacts had force maxima in the range of 1 N to 25 N with frequency and media size range. Once these parameters are set based on the type of contamination, the cleaning process can be executed.

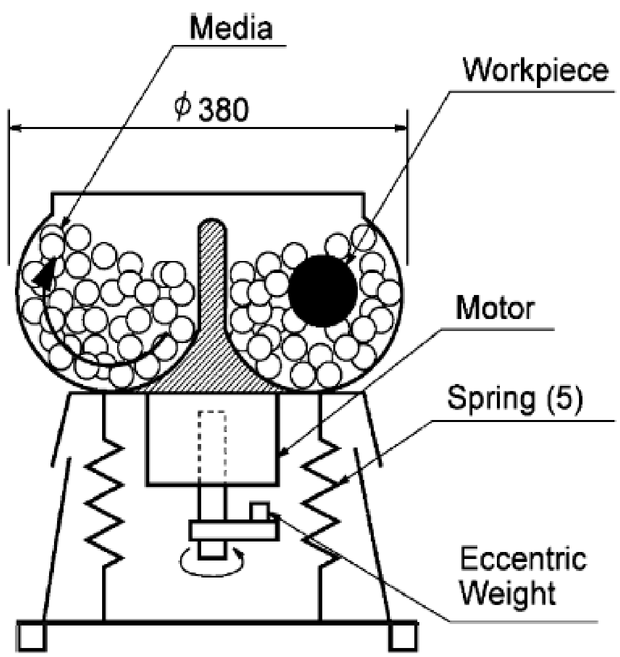


Figure 21 - Vibratory Cleaner [40]

As seen in the diagram above, kinetic energy comes from the spinning transfers to the media, causing the media to move in the container. Container motion limits of the media explain short time scales versus long time scales. That is, over long time scales, the media motion can be approximately described by a flow field. The short time scale is defined as the period of the container vibration and the long time scale is the time it takes for media to travel distances approximately equal to the container dimensions. A workpiece placed in the vibratory cleaning system generally sets in a long time scale with a low speed for soft cleaning and high-speed short time scales for rough cleaning. The workpieces are placed inside the container with the media and the kinetic energy of the media is imparted on the workpiece. If the machine is designed well and the process is controlled properly, the work done on the workpiece will improve its surface layer in the desired manner. Vibratory finishing is often performed with the addition of a liquid detergent and water in the container. Mainly these additives are used in vibratory cleaning: water, enzymes, terpene, organic ester, alkaline detergent, limonene emulsion. The effectiveness of these additives are shown in the figure below [40][42]. After strong chemicals are used, a water rinse step has to follow the cleaning process. Water rinsing can help the pH stabilization and clean small particles from the surface. It is critical that workpieces must be dried after the water rinse step, since oxidation is one of the major problems with this system.

Fluid Type	Trade Name	Part Cleaned	Contaminants Removed	Part Results	General Comments
Enzyme	CJ's Parts Washing Solution (16%)	Fuel Injector fly weight holder	Light oil	Excellent removal of light contaminant load	Steel parts can rust after cleaning, left parts oil free, heating would have accelerated cleaning
Terpene	Tarksol HTF 10 (5%)	Fuel Injector fly weight holder	Light oil	Excellent removal of light contaminant load	
d'Limonene Emulsion	Brulin-Naturesol Emulsion (15%)	Fuel Distributor Shaft	Light oil	Excellent removal of light contaminant load	
Organic Esters (soy and corn derivatives)	Biotechnology-Vertec Gold (100%)	Fuel Pump Main Case	Grease, dirt, oil, paint	Excellent removal of heavy contaminant load	Most aggressive of fluids evaluated, and can remove or soften some paints. It leaves an oil film on parts.
Alkaline Detergent	Rochester Midland-Cleanaire 1200 (2.25%)	Fuel Distributor Housing	Light rust, dirt, light grease	Excellent removal of heavy contaminant load	

Table 6 - Vibratory Cleaner Solvents List [41]

The process parameters in vibratory cleaning are aspects of the process that affect the media workpiece. The parameters of media are hardness, shape, and density. The frequency of rotation is usually in the range of 40 ± 20 Hz depending on hardness of the material. For soft materials, lower frequency would be more suitable. Solvent types are shown on the solvent list. Therefore cleaning can be designed for each type of material and contamination.

Advantages

- System can remove light rust and oxidation without harsh chemicals.
- System shows good performance on heavy layers of caked dirt
- With correct media type delicate parts can clean
- Generally, chemicals are not used
- It is an automatic system, therefore labor cost is low

Disadvantages

- Noise level is much higher than other cleaning processes
- Can’t easily remove heavy rust, grease and contaminants
- Difficult to take small parts out of the system
- For heavy dirt cleaning process cycle time is fairly long (over 30min).

Emission and Environmental Health and Safety: The vibratory process waste consists of contaminants and metal particles from the parts, contamination, and media. If additives (water, enzymes, terpene, organic ester, alkaline detergent, or limonene emulsion) are used in vibratory cleaning then the system produces a sludge that is a combination of metal particles, contamination, and fine particles from the media. There may be material from the parts that will classify the sludge is hazardous waste. System waste has to be tested before solution to find how waste will be discharged. Test results show that for some of the additives, waste can be sent to a distiller for reuse or sent out as waste. After a certain time, media has to be renewed. This material can also be considered waste material. When additives are used, the system operator must avoid skin contact with them, because contact may cause dermatitis or irritation. Some of the products have a somewhat strong odor, so the cleaning system may need to be accompanied by ventilation. However, the resulting waste from the wet cleaning method will be the cleaned contaminant as a liquid or solid. Thus the operator has to clean the cleaned contaminant carefully to prevent odor. After the operator takes the contaminant out of the system, it has to be analyzed initially to determine if it demonstrates the characteristics of hazardous waste. If the wet process is used, the waste will be considered hazardous waste. If a dry process is used, the waste might not include any hazardous types of material. During a cleaning process that contains heavy metals as the main contaminant, the ash may need to be handled as hazardous waste. Another weak point of the vibratory cleaning is the noise problem. When the system is started, noise pollution can reach really high levels. Therefore operator has to consider the working condition of the system and use ear protection. In the mean time, the system room has to be isolated with noise walls [41][42][43].

Cost: There are a few types of vibratory cleaning equipment available to remanufacturers. Costs mainly change depending on the size and features of the system. Systems can be designed for large or small quantities; in parallel with part quantity, system can range from $3,000 to $20,000 for vibratory cleaning systems [41].

Energy consumption is approximately 0.1kw to 0.2kw, which is quite low per cycle. But we should consider Vibratory cleaning is not enough to clean by itself the parts [41].

Performance: Vibratory cleaning systems, both wet and dry, have been used with success in different types of industries. Wet and dry methods can be used with the same type of system. These methods are not effective enough to clean different contamination types. Additive chemicals are needed to improve the effectiveness of cleaning processes. Generally, vibratory cleaning is used with other types of cleaning methods. Vibratory cleaning without chemicals is generally used for finishing, hardening, and cleaning sharp edges of materials. Media type is one of the significant criteria for selecting a cleaning process. Plastic media is generally used for cleaning very fragile materials or as a carrier for polishing compounds in part finishing. The metal media are used where edge rounding or surface finishing by ceramic media cannot be tolerated. Media shape and size selection is also really important, and it has to be selected for the best cleaning and minimal media lodging in the parts. If parts have small holes, media should be small enough to get into the parts. Also media type can be mixed. Different sizes of media may increase cleaning efficiency. System and worker costs are much lower than other types of cleaning methods, because the system is really simple with no need to use extra equipment. The operator is needed for an electronic system and a 30 minute long system works automatically. Wet and dry method system settings are based on the cleaning result and thickness of the contaminant. The system scan be separated into methods by wet and dry vibratory cleaning process. The methods need to be correct in order to gain information on the correct setting needed to meet clearance levels. Results from experiments show that vibratory cleaning needs to be used with another type of cleaning process. Vibratory cleaning has to follow another process [41][43].

2.1.5 Thermal Cleaning

Thermal cleaning removes all types of organic contamination from parts by using a combination of oxidation and chemicals. Thermal cleaning systems are generally used on cork gaskets, resins, paints, adhesives, oils, plastics and greases on metal surfaces that are burned to ash in an oven. Thermal cleaning can be the second part of another cleaning process [44][45]. Ash and dirt needs to be cleaned from a part's surface, dry blasting may be the first step of that cleaning process. After the selected first step, the second step is to remove both residuals from the thermal cleaning operation as well as metal oxidation layers created by the thermal process. Also this process removes all oil from the surface of the workpiece. Typically, shot blasting or immersion cleaning is performed to return parts to their original condition, so this second step design is based on contamination type.

System of Process: The first step in the thermal cleaning process is to burn organic materials on the part surface and converts it to ash and gases. The thermal cleaning process has really strong effect on decomposition and oxidization of heavy grease, rubber seals, gasket material and paint from the surface. This system is also useful for cleaning undesirable wires and melting solder joints. The thermal re-manufacturing system uses two types of thermal ovens: convection and open flame [46]. *A convection oven* is a flameless, insulated oven that is heated by burners from the bottom. The parts are not exposed to flame and heat up gradually as the oven heats up. Depending on the size of the oven and the quantity of parts being cleaned, the cleaning cycle takes between 1 to 4 hours [46] [47]. Temperatures for cleaning ferrous metals are about 700°F. Aluminum, which softens at about 650°F, is cleaned at about 450°F [44]. *An open flame oven* is like a rotisserie. Parts are mounted in a cage that avoids hot spots by slowly rotating the parts directly over a flame. The average temperature of the flame is about 1100°F, but the temperature of the air inside the oven is only about 500°F, allowing aluminum and ferrous metals to be cleaned together. After about 10 minutes of exposure to the flame, the flame goes out and a 20-minute baking cycle begins [46][47]. The total cleaning cycle lasts about half an hour. With the use of an air blower, contaminants can be cleaned from the surface more easily.

Thermal cleaning involves two different types of methods: Dry Thermal Cleaning and Wet Cleaning Methods [48]. Dry methods of cleaning are used in boiler units of high power to clean flue gases from fly ash, and are mainly electric precipitators that provide cleaning efficiency. Wet methods of flue gas cleaning are widely used in boiler units of small and medium power. A common feature is the use of special tubes for intensive spraying of water (chemical additives if needed) by a gas flow moving at a high speed of 40-100 ml/s [48]. An ash collection efficiency of 96-97 % may be achieved, with the water resistance of these ash collectors and temperatures of leaving gases that are acceptable for the power plant operation. The workpiece has to be rinsed after the wet method if chemical additives are used.

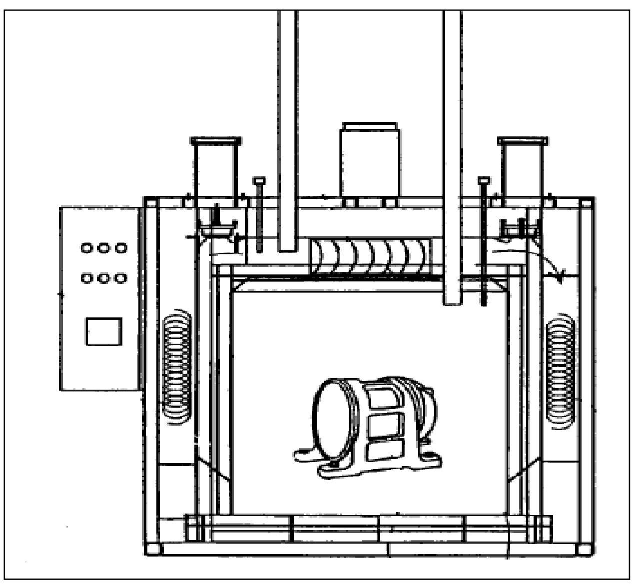


Figure 22 - Thermal Cleaning [49]

The dry method of cleaning is more common than the wet method in industrial activities. Both of the methods need a second step of cleaning. After the thermal process, air blasters are used to take the burned contaminants off the surface. Air blasting speed is set based on chemical type and material type. One weakness of the thermal cleaning process is that an undesirable softening of materials and high pressure after cleaning might affect the shape and condition of the workpiece [49]. While setting up the system design, material type and contamination characterization have to be analyzed correctly. After air pressure is applied, a shaker (tumbler) removes shot and quickly cools the parts to a safe handling temperature with a blower. The last step of thermal cleaning is washing the part with a hot tank or low velocity spray wash tank. As mentioned before, thermal cleaning is used as a second part of cleaning process. Thermal cleaning can be the second part of a cleaning process with dry blasting as the first step. Obviously, thermal cleaning alone is not sufficient to clean all the contaminants from the surface.

Chemical Vapor Decomposition: The CVD method enables the growth of an SEG layer at temperatures below 700 C. However, in the CVD normal procedure, in situ preheating, typically above 700 C, is nominally carried out to remove native oxide or hydrocarbon contamination on the surface before performing epitaxial growth [50].

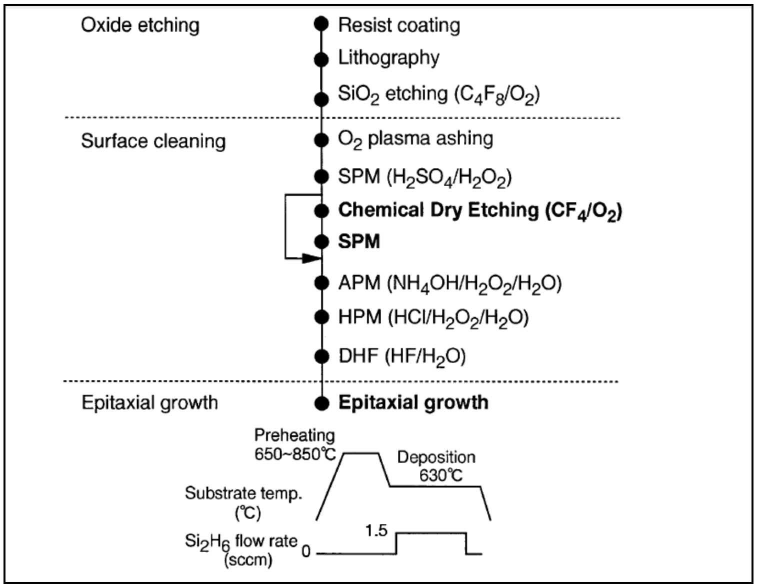


Figure 23 - CVD Cleaning Steps [50]

In this study Si2H6 selected for SiO2 film were used. Flow rate as shown on the graph 1.5 sccm. SiO2 film is etched by electron cyclotron resonance C4F8/O2 plasmas through a 150% over etch step. This step is carried out under the following conditions: the total gas pressure was 0.1 Pa with C4F8 and O2 flow rates. Surface is removed by an O2 plasma treatment followed by an H2SO4/H2O2 (SPM) wet treatment. The CDE using CF4/O2 was carried out in an anode powered parallel plate plasma reactor system. The etching time was set at 40 s. The CF4 and O2 flow rates were 143 and 58 sccm, respectively, and the total gas pressure was 100 Pa, when the Si etching rate was 30 nm/min. Wet cleaning treatments by using the NH4OH, H2O2, and H2O mixture (APM). HCl, H2O2, and H2O mixture (HPM) were used to remove particles and metal contamination. The dipping time for both treatments were 10 min. Diluted HF (DHF) with the HF to H2O was used to remove the native oxide layer. The preheating temperatures were varied from 650 C to 850 C for 10 min in the growth chamber. The growth temperature was kept at 630 C. The Si2H6 flow rate was kept at 1.5 sccm, and the pressure of the growth chamber during growth was kept at less than 3 $x10^{-3}$ Pa [50].

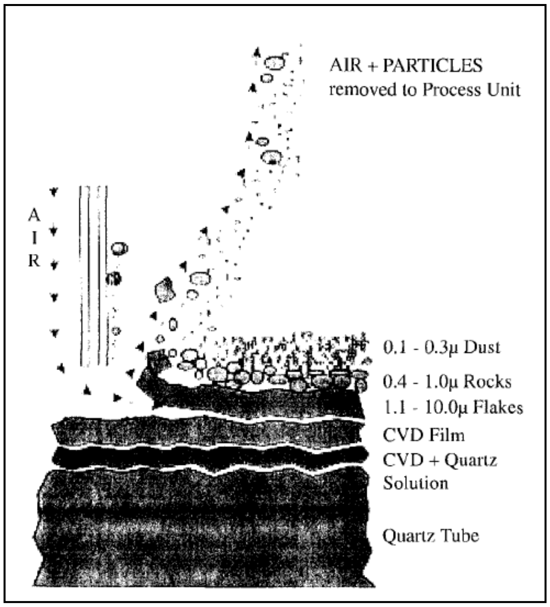


Figure 24 - Cleaner/Deposition Interface [51]

Advantages

- System can be designed for large number of workpieces cleaned simultaneously
- Cost of cleaning process is quite low
- Energy consumption is low
- Generally, chemicals are not used
- System can clean several contaminants and insulation: oil, grease, paint, gasket, rubber, etc.
- Labor cost is low

Disadvantages

- Subsequent treatment is required to remove ash and/or rust from part surface
- Flash rusting of some parts may occur after the cleaning process
- Undesirable softening is observed on some aluminum parts
- If chemicals are used for cleaning, a rinse is required and generates waste

Effects of Thermal Cleaning on Hardness: Thermal cleaning can alter the workpiece if the workpiece material has a low melting point (zinc or aluminum). The cleaning process setting is based contamination type. If the contamination needs to be cleaned at a high temperature, the melting point of the workpiece material can become a big problem for this process. Steel may be softened below its limit and may lose its hardness. For different materials, hardness change versus thermal cleaning temperature graph is represented here. Also, after the workpiece is exposed to high temperatures, the dimension of the part might change which makes the part unusable. On different kinds of engine parts, test results were shown and results were converted Rockwell A type. For hardness reading Rockwell A type is used for cover C and B scales, (Rockwell C 60 = Rockwell A 81 and Rockwell B 80 = Rockwell A 49.5) [44]. This information is represented on the Figure-25 below.

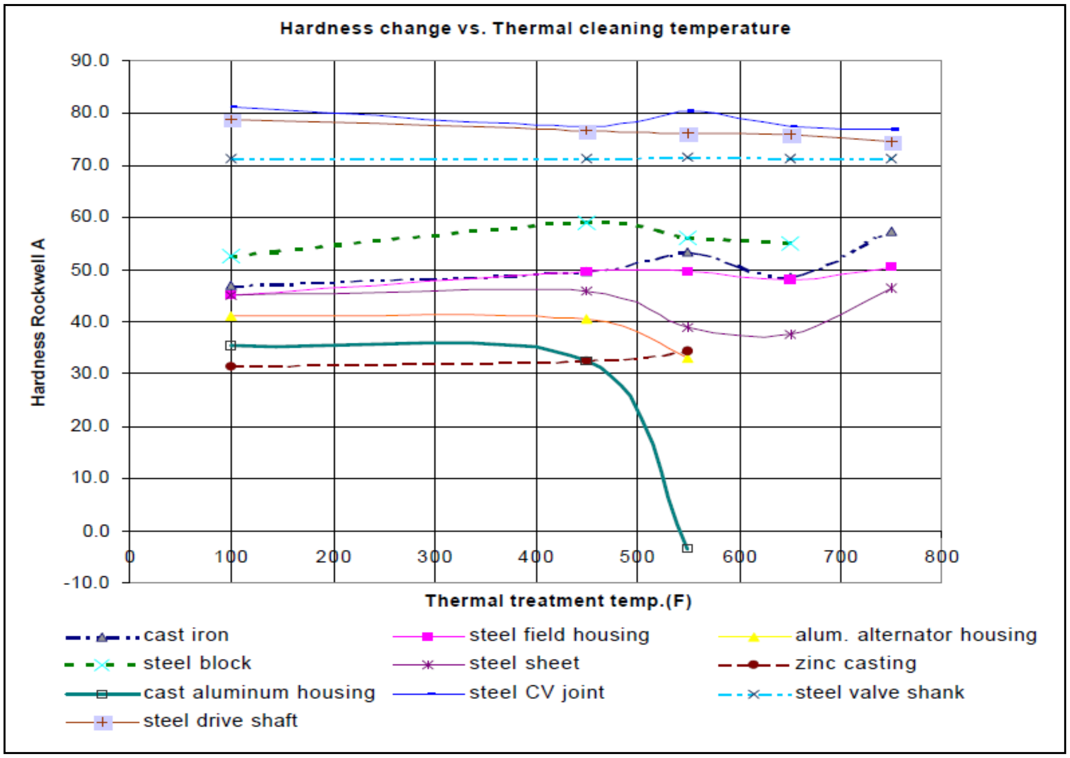


Figure 25 - Hardness change vs. Thermal Cleaning Temperature Graph [44]

Emission and Environmental Health and Safety: Waste materials generated from both type of ovens consist of the carbonized products of the contaminant and undesirable materials on the parts cleaned. Contaminants and undesirable materials contain ash and flue gases created from the oxidation [44]. The system has to clean the gases and keep it in acceptable air emission standards. During the process systems burns the contamination and carbonizes heavy metals and other dangerous materials on both type of cleaning processes. Thermal cleaning system does not create hazardous waste by itself, when chemical additives used and make another hazardous type of reaction with contaminant during the processes. Even if chemicals are not used, during the burning and carbonization process system produce hazardous waste. If the wet cleaning method is used, the system does not make as much dust as dry cleaning method. Wet cleaning method will be the melted contaminant as a liquid or solid and generally after that contaminant stuck in the system like a gum. Thus the operator has to clean ash or melted contaminant carefully to prevent it. After the operator takes the waste out of the system, the ash has to be analyzed initially to determine if it demonstrates the characteristics of hazardous waste. If the wet process is used, waste will be considered as hazardous waste. If the dry process used, waste might not include any hazardous type of material. During a cleaning process that contains heavy metals as the main contaminant; the ash may need to be handled as hazardous waste [44][46].

Cost: There is a wide variety of thermal cleaning equipment available to the remanufacturers. Costs mainly change depending on the size and features of the oven type and additional equipment needed. The least expensive units are simple bench-top cleaning systems [45]. Systems can be designed for large or small quantities; in parallel with part quantity, ovens can range from $8,000 to $50,000 for convection ovens. Rotisserie ovens can range from $11,000 to $32,000. Installation cost and the cost for additional parts can change with the size of oven [44].

Energy consumption is approximately 1.14kw/kg blast and 1.52kw/kg blast, which is quite low with good 0.3 to 0.6 Kw per cycle cleaning result [44] [45].

Performance: Thermal cleaning system, both wet and dry have been used with success in different types of industries. Wet and dry methods can be used with convection and open flame ovens [44]. These methods are quite effective on different contamination types. Chemicals are needed if the thermal cleaning process is the only cleaning method for an industry, but it uses as a flue gas [45]. Generally, thermal cleaning is used with other types of cleaning methods. Thermal cleaning removes all types of organic contamination from parts by using a combination of oxidation and chemicals [44] [45]. Also, system and worker costs are much lower than other types of cleaning methods, because system doesn't have extra chemical cost, trained worker with using electronic system and extra system equipment. Wet and dry method system settings are based on the result of ash waste analysis. This study separates the methods by wet and dry thermal cleaning process. The methods need to be correct in order to gain information on the correct setting needed to meet clearance levels. Results from experiments show that thermal cleaning removes all kinds of organic contamination from parts by oxidation and chemicals.

2.1.6 Molten Salt Cleaning

Molten salt cleaning is a common surface cleaning process that has been widely used in industry for remanufacturing processes. Molten salt cleaning processes are applied in the cleaning of used components in preparation for remanufacturing. Molten salt cleaning is the one of the most effective methods of removing soiling particles of different materials and sizes, and films and coatings from solid surfaces. The biggest advantage of molten salt cleaning is that it is effective on all types of parts, including those with small holes and those that are hard to clean. Batch and workpiece size do not present major barriers with that cleaning method. The size of the bath can be designed depending on batch and workpiece size. Molten salt cleaning has proven successful in the cleaning of sand, scale, shell, face coat, oils, soils, carbon, paint, inorganic materials (chemically reactant), and organic contaminants. The most commonly used salts are alkaline nitrates, such as sodium nitrate, sodium hydroxide, potassium nitrate and potassium hydroxide, with sodium nitrate and hydroxide being the most popular [52][53]. If system cleaning level has to be summarized, this cleaning system is generally effective on every kind of contamination level but is mainly used for middle and high level contamination.

System of Process: In the molten salt cleaning process, the main material is the salt and processes are based on mixtures of inorganic salt compounds heated to melting temperature or above their melting points to form a working fluid. Salt features have to be checked before being used, because factors including the operating temperature range, chemical reactivity, and performance have to be fit for the material and contamination type. The inorganic salt compositions are heated to temperatures above their melting points to form the working baths, heating a metal above its melting point to form a liquid. During the process, molten salt has a unique side for which there are no solvents that can be used for working fluid. In fact, the system's biggest advantage is that it does not need solvents. Therefore, the system does not create evaporative losses, fumes, or odors from the molten baths during operating temperature [53]. Only during the actual reaction processes are there any gaseous emissions from the bath.

Utilizing molten salt cleaning with metals has a variety of advantages when used in industry. System design is dependent on the components of the salt used in the bath process, contamination type and features of the material being cleaned. In parallel with these design parameters are the capacity of heat transfer and/or chemical processing system where reactions occur within the bath. During the surface treatment, the process results in fundamental structural changes in the part, with enhancement of surface hardness and wear resistance. Based on these parameters, the system is categorized based on three different types.

The first type of process uses molten alkali metal nitrates or a mixture of nitrate ions. Those processes with nitrites are often used where temperatures in the range of 160 - 550°C are desired. This system uses carbon and carbon alloy in addition to steels, treated in the heat treatment of a range of aluminum alloys. Nitrate salt baths also have uses in the vulcanization of rubber and in burning off polymer residues. Molten nitrate salts should not be heated over 550°C. At that temperature, salts will reaction oxygen to liberate, and this reaction may cause an extreme explosion. Molten cyanide baths are the second type of bath used for hard surface cases on parts subject to wear. These baths and their operating temperature are in the range of 800 - 950°C. System design is based on two factors: depth and nature of the case. The last type of molten salt bath type uses molten chloride salts in various types of tempering processes or as neutral rinse baths to remove adhering cyanide or nitrate salts while maintaining the work at high temperatures. System operation is generally designed to be in the range 700 - 1100°C. This process employs the use of forced air circulation furnaces that appear to be replacing salt baths. Rapid heating of the work piece and protection from atmospheric oxidation during and after treatment is the biggest advantages of molten salt cleaning over other processes.

The impactful reactions of molten salt baths make the system one of the most effective methods of solving common cleaning problems. Oxidizing molten salts rapidly remove organic materials, chemically react with inorganic materials, solubilize glasses and slags, and convert metallic oxides [54].

Molten salt bath cleaning is a fast and effective process when used in preparation for remanufacturing. This system uses a full active chemical melt without solvents, diluents, or water involved. There is no evaporation or loss from the bath; vapor pressure at normal operating temperatures is negligible.

Molten salts' high heat capacity makes allows the system a significant advantage over traditional cleaning methods. Generally molten salt types have a heat capacity around 0.5 (water = 1), which makes salts an excellent heat source. The bath acts to absorb the heat and then uses it when needed for starting a reaction or maintaining it during the process cycle. The high heat transfer rate is one benefit of this cleaning process because of the high chemical reactivity of the bath and very short cycle times. This system can clean every type of component geometry without any distinction.

The main types of organic contaminants present on used components are: oils, soils, greases, paints, and carbon. Their unique difference is that they quickly and completely change to inorganic compounds. This changing process happens with thermo chemical oxidation. Light film and soft contaminants can vaporize easily and leave the surface quickly. Thick metal scales such as rust and heat scales are not removed, but any organic oils or soils are removed during to process. This increases the efficiency and effectiveness of chemical brightening or pickling operations after salt bath cleaning.

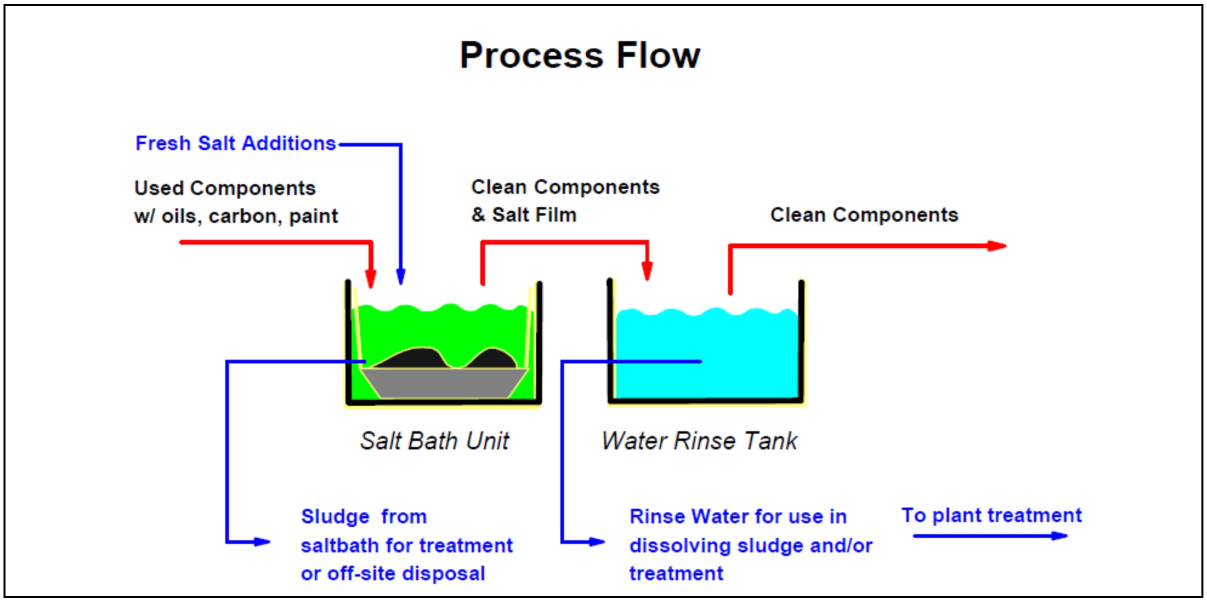


Figure 26 - Molten Salt Cleaning Process Flow [52]

Applications of salt baths in the wire industry have been studied by R.H. Shoemaker [53]. This study shows all the cleaning processes with chemical reactions. When oil and grease are cleaned, organic compounds are chemically oxidized in the following reactions:

(1) C+2Na NO3 => CO2+2NaNO2 (800F)

(2) NaNO2+0.5O2 => NaNO3 (800F)

(3) CO2+2NaOH => NaCO3+H2O

Oxidation of the nitrate formed in the reaction is shown in the first reaction. The carbonate formed in the reaction is represented with the third reaction and it is removed as sludge on a continuous basis.

Dry film lubricants such as molybdenum disulfide and graphite are removed in the salt bath by the following reactions:

(4) MoS2+6NaOH+9NaNO3 => Na2MoO4+2Na2SO4+9NaNO2+3H2O (800F)

(5) C+2NaOH+NaNO3 => NaCO3+H2O+NaNO2 (800F)

The metal oxides are conditioned with the following reactions:

(6) $2AO+2MO+2NaNO_3 \Rightarrow A_2O_3+M_2O_3+2NaNO_2$ (800F)

(7) $2M_2O_3+4NaOH \Rightarrow 2Na_2MO_4+2H_2O$ (800F)

(8) $NaNO_2+0.5O_2 \Rightarrow NaNO_3$ (800F)

In the above equations, A and M represent the main metal elements in the metal substrate. Reaction seven represents oxide solubility in the molten salt.

The chemical reaction between oxidizing salt and the metal oxide is shown below:

(9) $2AO+2MO+2NaNO_3 \Rightarrow A_2O_3+M_2O_3+2NaNO_2$ (800F)

Reaction nine describes a conditioning reaction and metal rich oxides being reacted with the available oxygen to produce an acid soluble compound. The pickle acid rate is reduced in concentration, and can be realized through this change. The conditioned oxide has to be completely removed for the following salt bath treatment. The composition and concentration of these acids varies with the major alloy being processed and the preference of the pickle house [55].

The next station for the work piece is a water quench. After a salt bath furnace, the outside of the work piece has a very low pH. In order to prevent harm to the main material of the work piece, pH has to be stabilized with a water quench. This water quench process will also make cracks on contamination, which are hard to clean. Depending on the quench sensitivity of the work piece material, cooling down or direct quenching has to follow. After water rinsing, there will be a thin, tight iron oxide coating on ferrous materials.

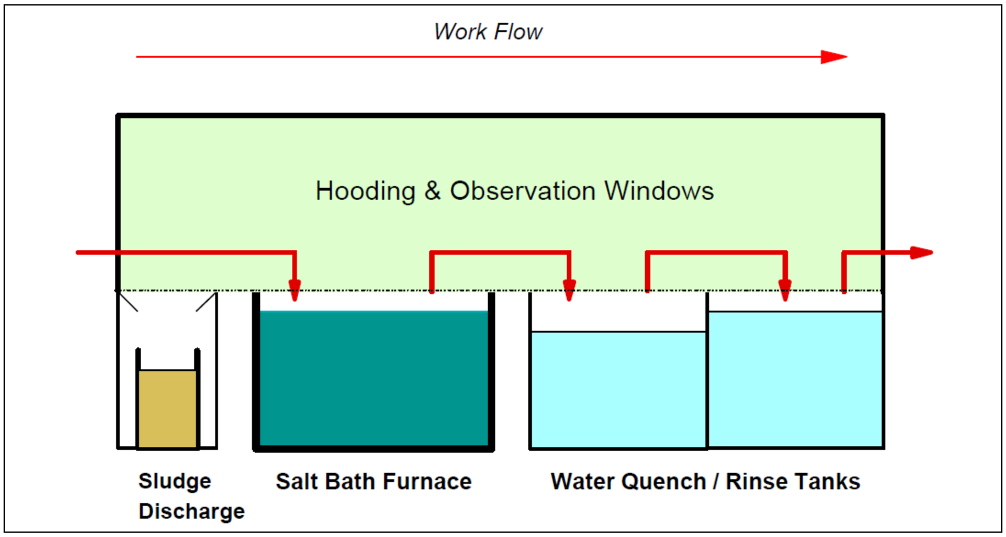


Figure 27 - Molten Salt Cleaning Work Flow [52]

The cleaning process, which has been explained above, is summarized in Figure-27, which is shown below. In teardown, the pieces are taken apart and each part has to be processed and analyzed for contamination type. Then the cleaning process is selected as described above, depending on contamination and material type. Before the cleaning process starts, gross oils and soils are cleaned with steam or low-pressure water, followed by air or oven drying. The workpiece must be dry to avoid any reaction between water and salt. The salt bath is designed with the correct salt and process type. Post cooling processes are designed depending on material type, with water quench and rinse as the last step before acid pickling and brightening.

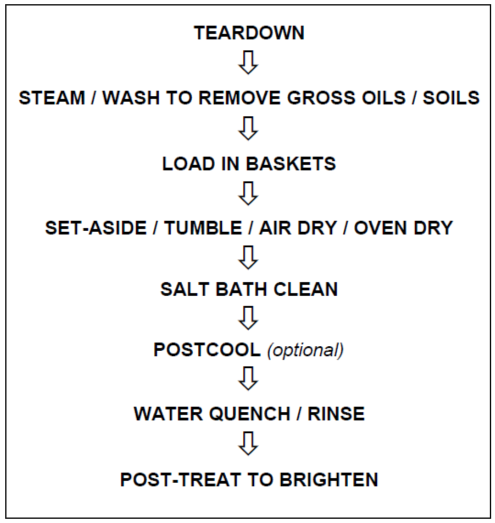


Figure 28 - Molten Salt Cleaning Process Flow [52]

Chemical post-treatments generally include acid pickling solutions to complete the cleaning process and produce a clean, metallic appearance.

Advantages

- System can remove really strong oil, soil and carbon contaminations.
- System shows good performance on heavy layers.
- System is effective on every geometrical type of workpiece
- System has short cleaning cycle

Disadvantages

- Strong chemicals are used
- Molten salt cleaning is not really effective on every type of inorganic contaminants
- Trained workers are needed
- For heavy dirt, cleaning process cycle time is fairly long (over 30min).

Emission and Environmental Health and Safety:The molten salt process produces contaminant waste in the form of a salt and water mix. The system does not require any additives or solvents, so sludge contains only a combination of salt particles, contamination particles and fine particles from the workpiece. There may be chemicals from the chemical salt reactions that will classify the sludge is hazardous waste. The carbonate formed in reaction is removed as sludge on a continuous basis. System waste has to tested to determine how waste will be discharged. When chemicals are used, the operator must avoid from skin contact with them, because chemicals may cause dermatitis or irritation. Some of the reactions create a strong odor, so for that system, ventilation is required. The resulting waste from the cleaning will be the cleaned contaminant, thus the operator has to clean sludge carefully from sludge tank. After the operator takes the sludge out of the system, it has to be analyzed initially to determine if it demonstrates the characteristics of hazardous waste.

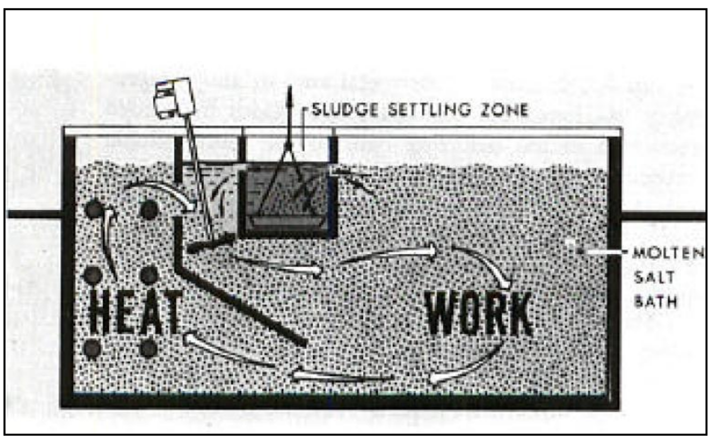


Figure 29 - Sludge Collection System [53]

Water rinse and water quench systems make another type of waste. It similarly contains salt, water and workpiece material particles. When the part is quenched, some of the part can crack and small pieces of the work piece material are contained in the waste of the water process.

Water rinsing waste has thin, tight iron oxide coating on ferrous materials. After each cleaning process, salt has to be removed from the system and it has to be washed before a new cleaning cycle is started. If the system also has a post treatment for brightening, some other types of oxides and chemicals will emerge from the system. All these waste have to be analyzed before being recharged to determine if they contain any type of hazardous waste [52] [53] [56].

Cost: Molten salt bath cleaning equipment comes in a standard set to the remanufacturers. Costs mainly change depending on the size of the system. Systems can be designed for large or small quantities; in parallel with part quantity, system can range from $9,000 to $60,000 for molten salt cleaning systems [52] [57].

In many instances, the energy requirements for a molten salt cleaning system are actually less than hot boiling aqueous cleaners they supplant [52]. Energy consumption is approximately 0.1kw to 0.2kw, which is quite low per cycle [57].

Performance: Molten salt processes are capable of removing all of the organics and soils that may be present on used car, truck and plane engine parts. It will quickly remove the remainder of any oils, sludge, and paint left on the component after minimal pre-cleaning, and at the same time, completely digest high-temperature stable deposits such as coke and carbon. While not capable of completely digesting gasket materials, it does degrade the gasket-to-metal bond [52].

Ferrous components are the most common parts to be cleaned in molten salt. Select non-ferrous parts such as aluminum can be successfully cleaned, but it should be noted that the temper or hardness of the aluminum will be reduced because of the bath’s operating temperature of 700 - 800°F [52]. If the design of the component is such that the reduction in temper will not adversely affect it in service, it is a good candidate for salt bath cleaning. Certain metals such as magnesium or zinc die cast may not be processed in an oxidizing molten salt. Magnesium will ignite and burn, while zinc die cast may exhibit excessive surface blistering as a result of dissolved gasses building up pressure.

2.1.7 Immersion Cleaning

Immersion cleaning is a common surface cleaning process that has been widely used in industry for remanufacturing processes. This process is the one of the most suitable methods of removing soiling particles of different materials, films and coatings from solid surfaces. Immersion cleaning processes are applied to be used components in preparation for remanufacturing. This cleaning approach is particularly good for cleaning irregular shapes, box sections, tube and cylindrical configurations that cannot be penetrated using spray systems. Immersion cleaning has proven successful in the cleaning of oils, soils, carbon, rust, dirt and gaskets [58]. For cleaning, methyl ethyl ketone, methyl chloroform, and ODS (ozone depleting substances) based solvents are main type of cleaners.

Immersion cleaning refers to a group of the most applied cleaning methods for mechanical parts. It generally uses cleaners with high concentration. Using a convection current combined with external vibration, soils are removed from metal surfaces conveniently. The operation may vary from hand dipping a single part or agitating a basket containing several parts in an earthenware crock at room temperature to a highly automated installation operating at elevated temperature and using controlled agitation.

System of Process: An immersion cleaning system uses aqueous alkaline for the cleaning process. Immersion cleaning with agitation is the most widespread and effective system for removing contaminants. If there is significant oil contamination on the work piece, the cleaning system has to be designed to be suited to oil contamination. A skimmer system has to be installed on the first tank to skim the surface. This modification helps improve the cleaning result with extraction through an oil film when the workpieces are taken out of the tank [59]. A hot alkali spray cleaning and rinsing process uses cavities similar to the ultrasonic cleaning process mentioned in a previous section. If immersion cleaning is used together with ultrasonic cleaning, effectiveness is measured by the use of cavities. Cavities are filled with fluid and maintain consistent cleaning effectiveness throughout the cleaning process [60]. If ultrasonic cleaning is not included in the process, the main parameter becomes the makeup of chemical solvents. A cleaning spray component is a part of the immersion cleaning process. In order for the cleaning spray to be effective, the pressure must be set as high as possible without causing any damage.

A tray system or transport between other process steps must be rapid, and the air above the tanks should be humid. If systems use some bed odor chemicals, a closed system is used to obtain better control of the environment surrounding the cleaning line and therefore get a better result.

Rinsing is an important stage of cleaning and is used more than once in some types of immersion cleaning processes. If rinsing occurs between cleaning steps, it is to clean the chemicals from the surface of the workpiece from one step to the next. Soft water rather than pure, ultrapure or ionized water is ideal if rinsing between two steps. Depending on the process, soft, pure, ultrapure or ionized water can be used. Recycling can be used on the rinsing steps. A recycling system can be integrated into the cleaning system when using copious amounts of water to increase the efficiency without wasting water [61].

In some cases an additive may be added to the final rinse. For instance, a “flash rust inhibitor” may be added when cleaning steel. Acetic acid may be added to remove the “stain” on electroplated chromium when chromium is used as a basecoat [59].

Ultrasonic agitation can be adapted in any of the fluid tanks in the system to increase the cleaning result. As mentioned with the ultrasonic cleaning process, high power ultrasonic cavitation for some materials can fracture the surface and deform, erode, and micro roughen the surface of ductile materials. Therefore, the system setting has to be designed well if ultrasonic agitation will be added to the system to increase efficiency of the cleaning. Ultrasonic cleaning can change the results of the cleaning but if the workpiece was produced with soft material, ultrasonic cleaning might affect the shape of the workpiece or features.

The cleaning process finishes with a drying step. Undesirable residue on the surface has to be evaporated and cleaned during the drying step. This is achieved by blow-off with hot air or hot tunnel system along with movement of the workpieces so that the parts can be further dried.

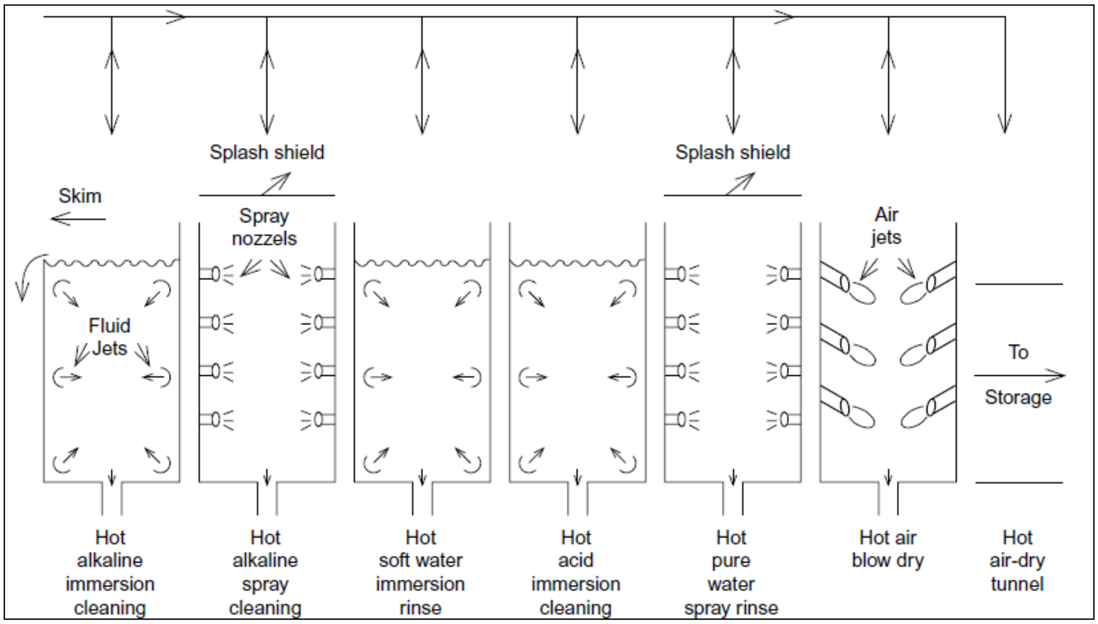


Figure 30 - A typical type immersion cleaning line for Metal Parts [59]

The process explained above is the main type of immersion cleaning process. Aqueous immersion cleaning can be effectively improved and designed for different contamination types. Using several different techniques either exclusively or together helps reach the goal of maximizing effective cleaning. The most common methods are discussed below [59].

1) Increasing temperature is the one of the most common ways to increase the effectiveness of the process. The contamination type has to be determined correctly and optimum temperature has to be selected. Optimum temperature for each situation that is selected by physical characteristics of the materials involved.

2) Agitation is the second important parameter to make improvements to the cleaning process. Movement of the solution has to run through and around the workpiece being cleaned. Agitation can be more effective with mechanical systems through the use of spargers, mixers, and rotating barrels, or mega or ultrasonic cleaning.

3) Electricity is another method of making large improvements. Electrocleaning should not be used as the initial cleaner to remove the bulk of soils, as mentioned in system of process, but should instead be used to remove smuts, light flash rust, light oxides and residues from previous cleaning operation [62].

Additionally, several cleaning machines and system approaches of immersion cleaning are summarized below:

Agitation Immersion Cleaning: Agitation cleaners generate mechanical energy to clean parts in two ways. The first is agitation of the cleaning fluid and the second is agitation of the parts themselves [63]. Agitation starts with putting work pieces in baskets or a cage while they are rotating or moving up and down on a platform. The platform moves as a result of either air pressure or electricity. Air pressure is more common that electronic systems. Electronic platform system agitation is more aggressive than air pressure system [61].

Immersion equipment may also utilize pumps to agitate the cleaning fluid in which the parts are immersed, rather than agitating the parts themselves. In some situations, agitating the parts by themselves is not sufficient for cleaning; therefore an extra system has to be integrated with immersion cleaning. In these situations, immersion cleaners include an ultrasonic wash stage in combination with parts and/or fluid agitation [61].

Agitation immersion cleaners can clean a wide variety of parts. However, parts soiled with contaminants that are especially difficult to remove may require cleaning in a machine that offers more mechanical agitation than an agitation immersion machine.

Belt conveyor Immersion: Belt conveyor cleaning systems are used with immersion cleaning and spray wash cleaning processes. The differences between immersion cleaning and spray cleaning are shown on the first figure. Either a belt will convey parts so that they can be sprayed by fixed nozzles, or a moving belt conveys parts through a reservoir of liquid in which parts can be immersed and sprayed by fixed nozzles. The spray wash cleaning process only has spray wash and forced air blow off. This makes the system less effective than immersion cleaning. The second figure shows how the belt conveyor is arranged for immersion washing and what makes the belt conveyor immersion cleaning better than most of the cleaning processes. This process is more expensive to implement, because the system has more steps, details and equipment. It provides more cleaning for workpieces that need it after changes and with extra equipment. The system starts with spray nozzles that remove loose material from the workpiece. The conveyor belt moves the workpiece down into a liquid cleaner and the system sprays the workpiece with high pressure. If needed, the part is heated by immersion in hot liquid. At the same time, the part is sprayed with a pressurized nozzle and put in contact with a cleaner liquid. Then the conveyor system takes the part out of the cleaner liquid. Parts will be rinsed with pure, ultrapure or ionized water and this water can be recycled from the cleaning system. The cleaning process finishes with a drying step, either a hot tunnel or hot forced air [64].

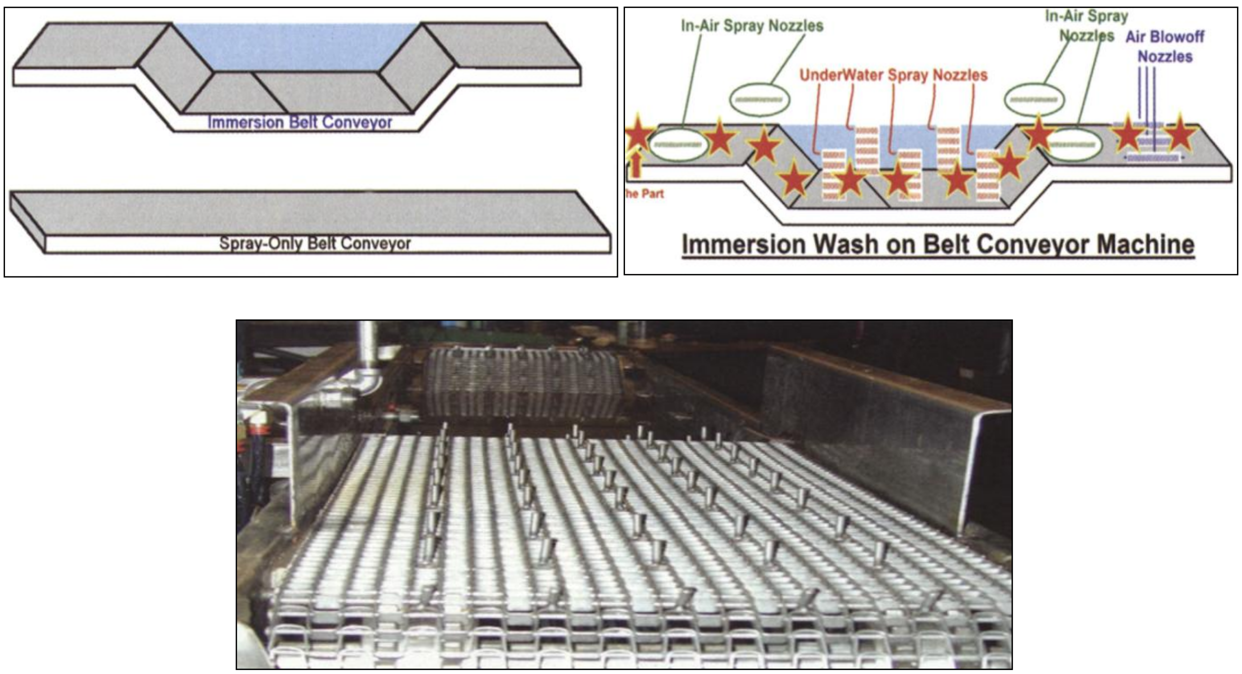


Figure 31 Immersion and Spray-Only Conveyor system difference b) Immersion wash on belt conveyor machine c) Belt Conveyor Immersion machine front view [64]

Rotating Drum Immersion: A rotating drum immersion machine is an alternative to a flat surface. Generally, rotating drum immersion machines are designed with tubes that can hold parts while they are processing. A helical structure of flights is designed to transfer small parts through the system. That is a rotating drum machine in its simplest form, which has the least cost. The workpiece is first rinsed with sprays in air, and then immersed in liquid for the cleaning process. The workpiece is rinsed first to loose tough contamination, and then clean the loose contaminants. The main difference between rotating drum immersion and belt conveyor immersion is the method of conveying parts. Belt conveyor and rotating drum machines look quite different because they convey the parts in different manners. Rotating drum immersion cleaning system is shown on the first figure. The outside of a rotary drum machine configured for immersion cleaning is shown on third figure. The perforations in the third figure allow cleaning or rinse liquid to be sprayed on the inside of the drum, and then drained through for recycling. The flights that can be seen in the front view on second figure [64].

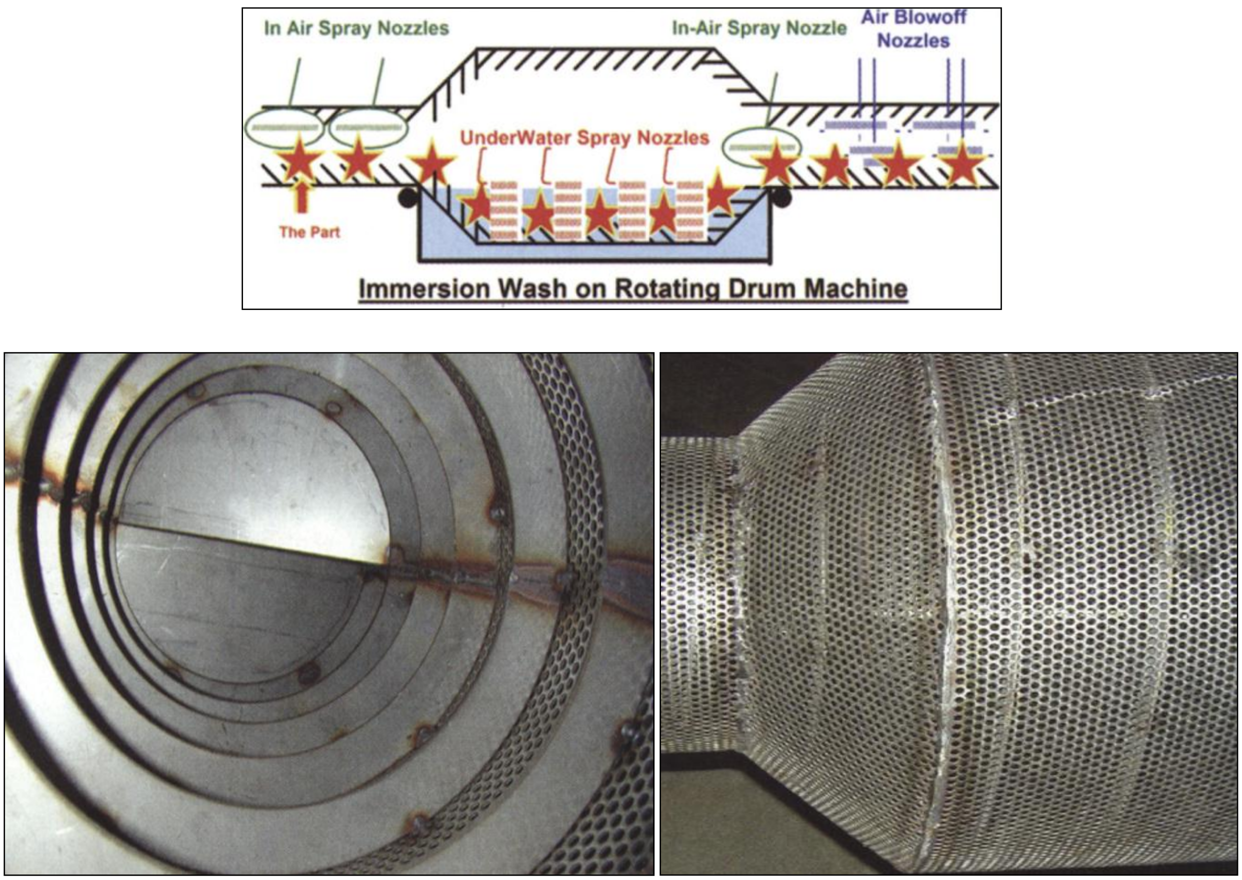


Figure 32 – a) Immersion wash on rotating drum machine b) Front view of rotating Drum c) Side view of rotating drum [64]

Belt conveyor systems and rotating drum immersion systems are shown and detailed above. Cleaning processes are based on the same system, but transfer of parts during the system is designed differently. These differences alter energy consumption. Another difference is that a conveyor immersion system is designed more for large workpieces, while a rotating drum immersion system is for small pieces. When designing the system for a certain type of part, part shape, size and number of parts must be taken into consideration.

Advantages

- System can remove strong oil, soil and carbon contaminations.
- System is environmentally beneficial, reusing water and chemicals.
- System is effective on every geometrical type of workpiece.
- System has lower capital cost.

Disadvantages

- Likely requires a large working area for the process machines
- May require repeated applications to obtain same results
- Rinse and drying step is required with aqueous cleaning to remove chemical residues.
- For heavy dirt, cleaning process cycle time is fairly long (over 30min).

Emission and Environmental Health and Safety: Environmental issues with immersion cleaning systems depend on the soils that are in the used water. Aqueous cleaners are also safer for workers because methyl ethyl ketone, methyl chloroform, and ODS (ozone depleting substances)-based solvents are the main types of cleaners. These chemicals are environmentally friendly. These cleaners are selected correctly according to contamination type [62]. Some of the contamination might have a reaction with the solvent, and make the waste hazardous. Therefore in experiments, waste must be sent to laboratories to ensure whether there are any specific cleaning needs for the waste. Some of the more aggressive aqueous chemicals used in immersion cleaning equipment are either strongly acidic or strongly basic, which results in some health risks [65]. The largest amount of waste comes from the water rinse and cleaning. Closed loop cleaning systems will still generate a waste stream at a greatly reduced rate compared to open loop systems. If possible, closed loop cleaning systems should be used because of environmental benefits. When system waste is recharging, it can be filtered which helps decrease the waste concentration. The waste may be in the form of contaminated filters and reverse osmosis membrane [62] [66].

Cost: Immersion cleaning equipment comes in a standard set to the remanufacturers. Costs mainly change depending on the size of the system. Large precision cleaning systems consisting of multiple tanks and drying stations with automated parts handling may cost $500,000. Typically immersion cleaning is a less capital intensive method of cleaning, so lower costs can be expected. The capital cost for medium and heavy duty immersion units will vary considerably, depending upon the unit type and its application. Capital costs for these systems can range from $5,000 to $85,000 [62].

In many instances, the energy requirements for an immersion cleaning system are actually less than most of the other traditional cleaning processes. Energy consumption is approximately 0.18, which is quite low per cycle [62].

Performance: Immersion cleaning processes are capable of removing all of the organics and soils from the workpiece surface. Immersion cleaning processes are generally preferred for parts with complex geometries (for example, with blind holes and undercuts) [66]. When the workpiece is immersed into the cleaning bath, contamination which adheres to that surface is dissolved by the chemical action of the cleaning agent. Rotating or swiveling the parts within the bath enhances the cleaning effect. Ultrasonic cleaning is also based upon immersion, and is capable of achieving high levels of cleanliness. Immersion cleaning is not designed to clean thick or heavy contamination types. The system has sufficient cleaning results on oils, soils, rust, coolants, grease, carbon, dirt, and gaskets [58]. It is generally used with low and medium thickness contaminations. The methods need to be correct in order to gain information on the correct setting needed to meet clearance levels. Results from experiments show that immersion cleaning needs to be used with another type of cleaning process if contamination is really thick and strong. Immersion cleaning is often used with another process in industry. Different types of equipment help to improve the system. The most common type of extra equipment is an ultrasonic system. If ultrasonic cleaning is adapted to the immersion cleaning system, that makes the system useful in a variety of industries [31] [38] [59]. Ultrasonic cleaning is discussed on section 2.1.2.

2.1.8 Brush Cleaning

Brush cleaning works with a soft and special type of brush that removes the contamination by applying a torque through the brush rotation. The pressure is another parameter that engulfs the contamination particles and the torque that solves the adhesion moment and removes the particle from a metal surface. Torque, speed and brush type can be set to clean different types of and get a better cleaning result. Brush cleaning is not strong enough to clean all the materials from the surface.

Brush cleaning is a widely used technique in the industry, generally used for chemical and mechanical polishing processes of metal surfaces. Effectiveness of brush cleaning in removing small particles depending on Van der Waals forces or chemical bonds. There has been research on other aspects of brush cleaning of oxide silicon wafers using PVA (polyvinyl acetate) brush, DI water, basic chemistry or surfactants [67]. These parameters also improve the effectiveness of brush cleaning if applied properly by optimizing the water flow, the rotational speed and brush pressure. Chemicals can be adapted to the system to increase cleaning efficiency of particle removal. Research shows that the brush pressure is one of the most important parameters in removing particles. The pressure increases the effectiveness of the brush that accomplishes the removal of particles.

Complete removal using the brush scrubber with deionizer water is achieved in cleaning thermal oxide silicon wafers. They showed that intermediate brush pressure, speed and time gave the best overall practice removal efficiency. High pressure and long cleaning time will cause more defects in substrate.

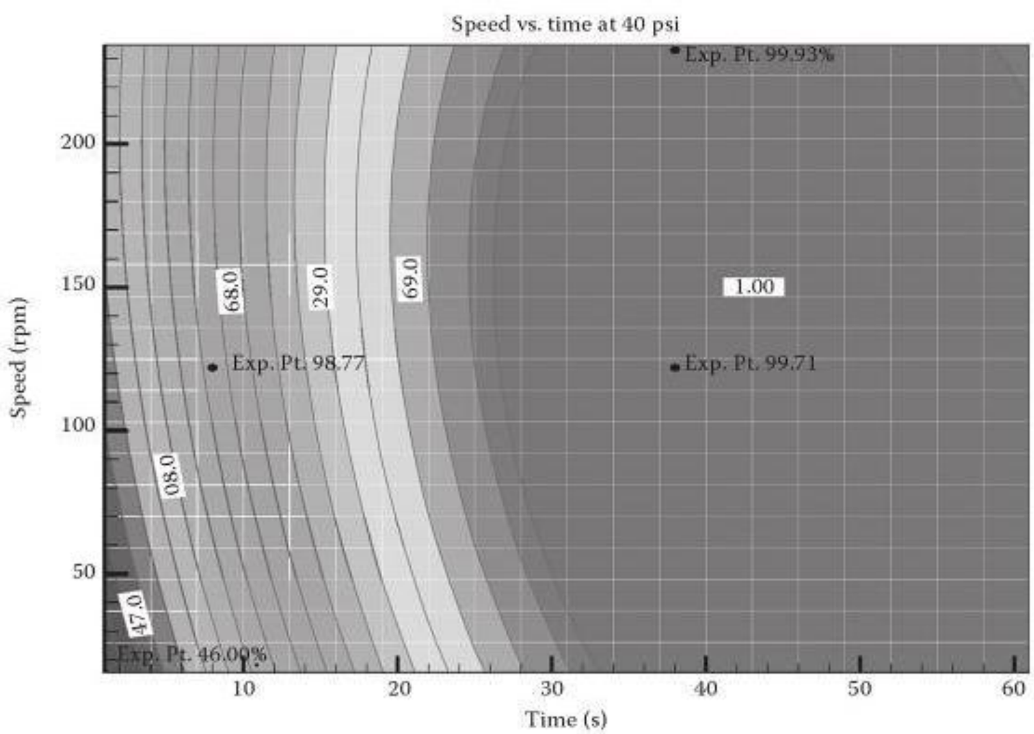


Figure 33 - Effect of Cleaning Time and Brush Speed on Brush Cleaning a PVA brush at 40psi pressure [67]

The figure above shows the effect of cleaning time and brush speed on brush cleaning using a PVA (polyvinyl acetate) brush at 40psi pressure between the brush and the substrate. The figure shows that the optimum cleaning time is longer than 30s at 40psi brush pressure [67].

2.2 Surface Contaminations

2.2.1 Classes of Contamination

Various types of contaminant occur in industrial cleaning applications that can be grouped into four categories. Inorganic contaminants, organic contaminants, complex contaminants and particulate contaminants are created these four different types of contamination group. The names of the contamination type indicate the characteristics of the soils in each group.

Organic soils include greases and oils and may be derived from petroleum, plant or animal sources.

Inorganic contaminants include salts and corrosion products and are usually produced by chemical reactions. Complex soils are a combination of organic and inorganic components. Particulate, or insoluble, contaminants are those which are solids and not easily removed using chemical methods alone [7].

Sources of Contamination: On cleaning process design determined workpiece contamination help for design parameter selection. Also chemicals and process machine settings are based on these information. Depending on contamination structure, it is even possible to simplify the cleaning process by recommending a change in the manufacturing process sequence. These type of changes examples can shown in the industrial process

For example, if the original cleaning application request requires removing carbon from a heat-treated steel part, the usual solution would call for an aggressive caustic detergent at high temperature (180° F.) and a rather long process time. On the other hand, if the parts are degreased before heat treating using a general purpose detergent at moderate temperature (130° F.) for a short time, the oil-free parts will not carbonize in the heat treating furnace. The result is a less expensive and safer cleaning system and a shorter process time [7].

Characteristics of Soil Types: The physical and chemical characteristics of the soils within each class are often quite similar to each other but may differ greatly from those in other classes. A cleaning process designed for a particular contaminant will probably also work for other soils in the same class but may prove completely ineffective for those in a different class [90].

Planning is the starting point of the effective cleaning and cleaning strategy requires an understanding of the characteristics of each soil type. After experiments contamination type has to categorized based on the figure which is shown on the below. Each soil type summarized and fitted cleaning process discussed before on cleaning processes.

Organic	*Inorganic*	*Complex*	*Particulate*
Oils	Rust	Fingerprints	Carbon
Grease	Corrosion	Paint	Silica
Resins (Uncured)	Plating salts	Ink	Dirt
Metalworking fluid			Chips & swarf

Table 7 - Soil Classes and Types [7]

Based on this information, piston surface has complex type of soil and it is harder to clean it. Based on these information on the surface contamination types, structure and wear types were analyzed.

2.2.2 Surface Contaminations Structure

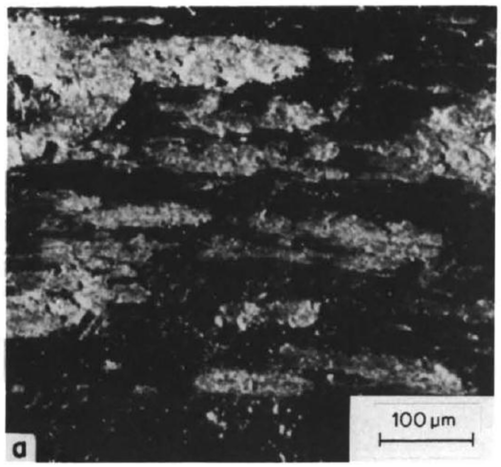
Organic Contamination: Contamination particles come from the surrounding air, oil, or other surfaces. The diffusivity of organic contamination is very high [68]. These types of contaminants can be found in every type of industrial deposition, which is a complex procedure. Another group of organic particles is the product or residues of incomplete combustion of organic fuel (hydrocarbon) in engines, which is called soot [69]. Also paint, oil, coatings and other types of organic contaminants and wear are summarized below.

Inorganic Contamination: Inorganic contamination types are highly common types of contaminants in different industries. Oxide scale, wear debris, dust, moisture, salt and inorganic lubricants are considered in this type of contamination. Inorganic contaminations are generally contaminated after organic contaminants. Characteristically, the first layer contains either organic or inorganic particles. After mixture, inorganic contaminants are found on the surface [69].

Figure 34 - Schematic Design of the Surface Contamination [86]

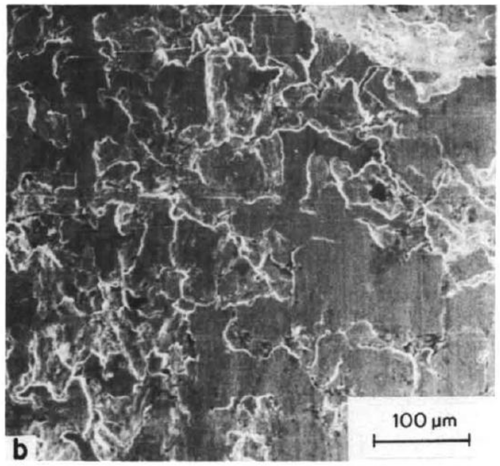
Hydrocarbons also create a wear on the surface. These particles come from organic fuel and are called soot. Lubricated oil and fuel, depending on their chemical constitution, can be the causes for soot wear [71]. The main problem with soot wear is that it can be connected with the oil particles and reach other parts of the engine. Soot's chemical constitution is such that it can cause engine system failure. The chemical composition carbon, hydrogen and oxygen forms a layer covering the substrate surface, which becomes thicker and larger as ageing increases [71]. Soot has to be cleaned with a suitable system, and the characteristics of wear on internal combustion engines have been studied. An abrasive characteristic and model is the most important and common type of wear. Other main and common wear types have to be considered to find an exact fit cleaning method for the engine parts and other type of mechanical parts cleaning process. Therefore adhesion, scuffing, abrasion, corrosion and bore polish are most frequently encountered on the cylinder and piston system. They are analyzed and shown with the micro pictures from the research of T.S. Eyre, K. K. Dutta and F. A. Davis [9].

Adhesion causes mainly welding and fracture of micro metal transfer from one surface to the other [9]. As mentioned before, the engine is designed and produced with cast iron and graphite. The most frequently used material is cast iron. Small particles of the material accumulate and create an adhesion type of wear. This adhesion is strong enough to cause system failure. The presence of graphite in cast iron prevents or limits adhesion.



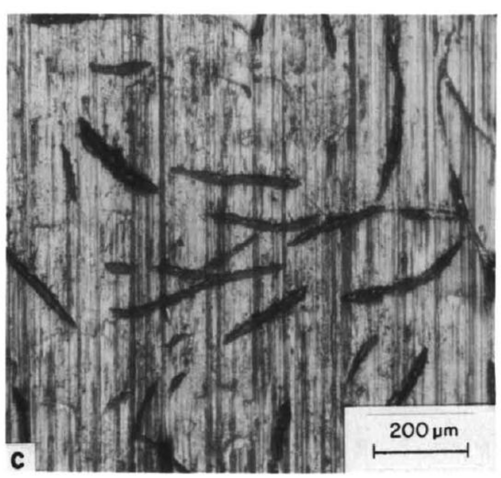
Adhesion Type of Wear

Scuffing is the process whereby deformation and frictional heating produces hot spots which transform into a hard layer. This is often referred to as the white layer, as shown on the figure above. The microstructure and high level of hardness provide strong evidence for high flash temperatures [9]. Scuffing has strong structure, which makes it difficult to clean when it causes problems during running periods. The white layer has been studied under two different structures, both low and high and include nital and sodium. Literature does not express agreement about the exact reason for scuffing.



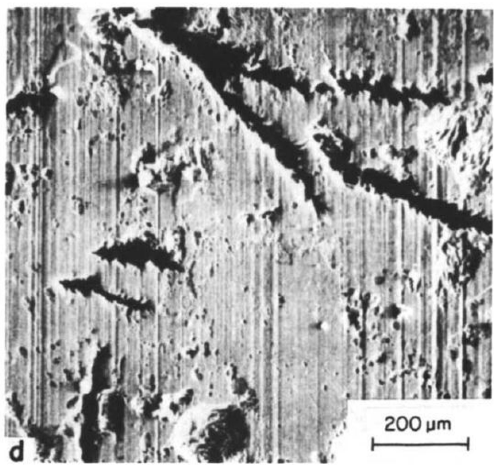
Scuffing Type of Wear

Abrasive wear is the most common wear mechanism observed on both engine and other type of mechanical systems. This type of wear is caused by hard particles on the oil film, and is shown in the figure above [9]. Abrasion is the strongest and most dominant wear type on the metal surfaces as shown on the figure. Once the original machining marks have been removed by wear, it is often possible to identify the graphite structure [79]. Abrasive wear structure, features, and model design are discussed below. Abrasive wear is the main wear type; therefore further research must be conducted to find the most suitable cleaning process for remanufacturing cleaning process.



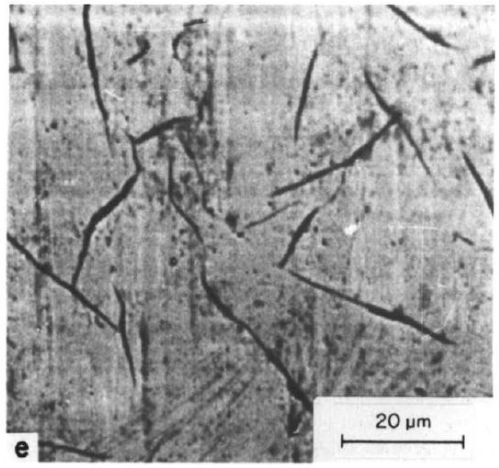
Abrasive Wear

Corrosion, which is a predominant wear mechanism in marine diesel engines, occurs as a direct result of the presence of sulphuricacid, formed by reaction between the products of combustion. It will usually be identified by its effect on the microstructure of the cast iron. Attack is greatest around the graphite flakes and at the carbide and phosphide boundaries. This results in the pearlite and phosphide shown on the figure being observed on the wear surface [9]. Corrosion is most common with marine diesel engines, because an acidic reaction occurs more quickly and easily in ocean water. If the salt ion stays on the any type of surface and reacts with oxygen, a corrosion reaction can start easily.



Corrosion

Bore polishing is a condition associated with turbocharged engines and can be influenced by certain design features. Catastrophic failure occurs when the polished areas of the bore is initiated. Bore polish can no longer be effectively lubricated, and scuffing is generally associated with very smooth surfaces. This is shown on the figure. This may be compared to the cast iron microstructure, as prepared using metallographic polishing techniques [9].



Bore polishing

When a contamination model is designed, all the factors are considered. The dust coefficient has to be considered with the different conditions and chemical constitutions around the work area of the engine. Dust type differs depending on work location, and standardized acknowledgement is used to generate a model like the Arizona Dust Test results.

The most difficult conditions can determined about abrasive wear, based on analysis of the literature review that in engines the oil film thickness amounts to 0-3 μm. Oil film thickness is conducive to the mitigation of solid friction and semi-fluid friction between the piston, cylinder and other type surfaces.

The majority of research considers abrasion to be one of the predominant kinds of wear in engine and other type of mechanisms. The process of abrasion comes into existence when incoherent or restrained abrasive particles are in the friction area. This kind of wear may be caused by rough jutting of a harder material. Abrasive wear in the presence of the abrasive material takes place when external debris as well as the products of wear penetrates between the sliding surfaces. Grinding particles from the air is the fundamental source of abrasive wear in the engine. Therefore, finding a method which would allow intensifying abrasive wear of automotive engine cylinders as a consequence of supplying them with air polluted by quartz particles is a problem of unquestionable practical importance [70].

Type of piece	Grade of dirt	Size	Weight (kg)
Piston	Incrusted solid carbon powder, oil and grease	∅500 × 750	439
Cylinder head	Incrusted solid carbon powder, oil and grease	1053 × 816 × 500	1300
Cylinder liner	Incrusted solid carbon powder, oil and grease	1250 × ∅652	750
Fire ring	Incrusted solid carbon powder, oil and grease	158 × ∅652	100
Exhaust manifold	Incrusted solid carbon powder	∅900 × 900	120
Turbo housing	Incrusted solid carbon powder	500 × 400 × 600	150
Turbo propeller	Incrusted solid carbon powder	400 × 400 × 250	130
Crankcase	oil and grease	1200 × 1200 × 3000	3000
Fuel pipes housing	Remains of fuel and painting	1200 × 500 × 180	78

Figure 35 - Engine Parts Contamination Types [72]

Solid carbon powder: Solid carbon powder is an agglomerate of fine coal dust rather than burnt fuel or oil compounds. This type of dirt occurs where there are exhaust gases such as in pistons, cylinder heads and always forms solid deposits which adhere firmly to the walls of the parts.

Oil and grease: These arise from engine oil and the additives of the various fluids that flow around the motor’s circuits. This type of dirt does not normally adhere as much to the part and does not include solid particles [72].

Oxide scale is a main corrosion product for all metal and alloys and has a variety of forms with different compositions. Its formation and growth mechanism, which is generally an electrochemical reaction procedure with the diffusion of corresponding elements, have been widely studied. The differences in the diffusivity of different elements make the oxide scale multiple layers [86].

Engine parts and metal surfaces are mainly focus on remanufacturing researches. If the technical condition is poor or fails on engine system parts, that affects the dynamic performance and economy of the engine, and also shortens its usage life. Currently, engines are made of nitrided cast iron or steel, and the piston is chromium plated. To survive an abrasive environment, other material combinations must be found. For economic reasons, this in essence means the use of hard wear resistant coatings deposited on conventionally fabricated parts [68][69]. The material of the engines had the following chemical composition: 0.25% Cu, 1.98% Si, 0.7% Mn, 0.19% Cr, 0.01% Ti, 3.29% C, 0.04% S, 0.08% P. The cylinders were made of grey cast iron, the structure of which contained pearlitic matrix and graphite flakes [70]. The engine parts have to be made of strong and reliable material. This affects the lifetime of the part, as well as contamination and wear from the material. When the engine works under high pressure and temperature, the parts might undergo ablation, which decreases the system condition.

CHAPTER III

CLEANING PROCESS MODELLING AND PLANNING

3.1 Process Categorization and Modeling

3.1.1 Categorization of Typical Cleaning Processes

The type of cleaning procedure that must be applied depends on the type of dirt. There are a wide variety of cleaning processes for different parts and these include:

Conventional cleaning: This is generally considered as a pre-cleaning process. Conventional cleaning includes the industrial cleaning machines that apply a pressurized cleaning solution to the part. The first process applied to the product is basically high-pressure hot or warm water and/or detergent with a specific cleaning additive. This step takes large particles from the surface and is considered a rough cleaning for weak contaminate layers.

Chemical Cleaning: Chemical cleaning consists of the application of an aggressive chemical product to the part in order to dissolve dirt. Molten salt, immersion, abrasive blasting and some types of thermal cleaning use chemical cleaners. The concentration of chemical cleaners has to be set to exactly fit the contamination type. Chemical cleaners that fit various contamination types are summarized previously in chemicals structure part of the introduction (1.2.2). Chemical cleaning can be improved through the use of pressure jets and by moving the tank. This mechanical effect increases the machine’s effectiveness and cleaning capacity. Cleaning temperature is also another significant factor to make chemical cleaning more efficient. The results observed with this type of machine are satisfactory for low and moderate levels of dirt. For parts with higher dirt levels, such as those with solid carbon powder deposits, satisfactory results are obtained through longer processing times [73].

Thermal Cleaning: Thermal cleaning is another alternative to chemical cleaning for parts that have carbon and hard oil contamination. Systems with contaminations such as cork gasket, resins, paint, plastics, grease, rust, or rubber seals can be cleaned with correct settings on the system. Thermal cleaning can be used without chemicals, so that surface contamination reacts directly with the flames. This type of cleaning is based on the fact that the solids contained in the solid carbon powder deposits disintegrate if all the components are completely burnt. Two different types of processes can also be used together. This is a three-part process: firstly, the part is heated and the solid particles are burnt; secondly, solid cleaned contaminants are taken from the surface of the part; thirdly, the solid granules are removed by shaking and blowing the mechanical part. If increased efficiency is needed, chemicals can be used on first step of the cleaning. In that case, a water rinse step has to be added between the first and second step.

The thermal cleaning procedure is widely used by diesel engine mechanics and is extremely effective. The disadvantages of this method are that the machines cannot be adjusted to the size of the part, and the purchase cost is high. In addition, the high temperatures which are needed in the process cause unacceptable structural defects in the parts during standard engine maintenance processes.

Mechanical Cleaning: The mechanical cleaning group includes wet and dry abrasive blasting, laser cleaning, ultrasonic cleaning, vibratory and brush cleaning techniques. These techniques are considered to be an extremely rough type of cleaning for mechanical parts. Mechanical cleaning has to set up correctly for the part type, because the strength of the system means that minor mistakes can cause big results.

Abrasive blasting is suitable for eliminating easily accessible contaminants, but parts often have small holes and tubes with bends, which are inaccessible and cause faults. Also some parts may collect abrasive particles that may later be released during operation. This makes abrasive cleaning unusable in some cases. While this process is sometimes essential, it cannot be considered a complete cleaning process.

Laser cleaning is separated into the steam and dry methods. Laser cleaning is one of the most effective types of cleaning for engine parts remanufacturers but as mentioned in the literature review laser cleaning part (2.1.2), steam laser cleaning is around 3 to 4 times more effective. This cleaning method is used without a water rinse step, and can clean the surface until it is smooth and ready to re-use.

Vibratory and brush cleaning techniques are other types of mechanical cleaning processes. These processes can be used before other processes to clean rough contaminants from the surface and make the part ready for the main cleaning process. They can also be used after the main cleaning process to make the surface smooth and shiny to send the customers. Ultrasonic cleaning is considered a mechanical process, but this process can use different types of chemical solvents. This makes ultrasonic cleaning both a mechanical and chemical mutual use process.

Ultrasound is an acoustic wave with a frequency which is above the limit of the human ear. Waves are selected by the contamination and workpiece material type. The figure is shown on Ultrasonic Cleaning (2.1.6) and waves are used at different levels in different industries. Ultrasonic cleaning is the way to use ultrasound waves in the water through a type of the transducers to get one of the greatest cleaning results.

Ultrasonic cleaning uses waves that are transmitted throughout the cleaning tank, producing a series of implosions in the water, a phenomenon known as cavitation. These implosions are what break the molecular structure of the particles and thus achieve uniform cleaning in the pieces, even in orifices and internal conducts in contact with the water, which are difficult to clean using traditional methods.

After categorizing the cleaning types, the major part of this thesis is comparison of the categorized cleaning methods. Comparison charts below represent all the main types of engine parts remanufacturers' cleaning processes. The technical specifications and settings are shown on the chart, separated by type of the cleaning. The chart also details effective contamination type, level, system type, workpiece material type, cleaning chemicals, temperature, cycle time, efficiency, system type, number of operator, system energy consumption, total approximately cost per part, system cost and emission.

Cleaning Types/Results	***Ultrasonic Cleaning***	
Principle Types	*piezoelectric • [32]*	*magnetostrictive • [32]*
Contamination Type	Paint/ Oil/ Carbon/ Grease/ Rust/ Oxidation • [31]	Oil/Carbon/Grease/Rust/Oxidation • [31]
Contamination Level	Low/Medium • [31]	Medium/Heavy • [31]

Cleaning System Type	Mechanical / Chemical • [35]	Mechanical / chemical • [35]
Processed Material Type	Steel/Aluminum/Plastic/Ceramics/Copper/Rubber/Iron / Refractory Metal / • [34]	Steel/Copper/Rubber/Iron/Refractory Metal /(ferromagnetic material) • [34]
Cleaning Chemicals	Brulin/ CAE/ Brew/ Optima/ Aemakleen/ Tarksol/ CO_2/ H_2O/ • [31]-[32]	Brulin/ CAE/ Brew/ Optima/ Aemakleen/ Tarksol/ CO_2/ H_2O/ Na_2SO_3/ Na_3PO_4/ Na_2SiO_3 • [31]-[32]
Temperature	70-180 F and 30 - 400 Hz frequency ultrasounds Ph=4.5-6.8 • [32]• [34]	100-180 F and 15 - 400 Hz frequency ultrasounds Ph=5.5-8.6 • [32] • [34]
Cycle Time	10-20 min • [31]	10-30 min • [31]
Efficiency	Steel,Iron-(Good) • [31] [33]Plastic-Ceramics-Copper-Rubber-Aluminum(Excellent)	Steel,Iron-(Excellent) • [31] • [33] Plastic-Ceramics-Copper-Rubber-Aluminum(Good)
System Type	Manual / Automatic • [31]	Manual / Automatic • [31]
Number of Operator	1 or 2 • [31]	1 or 2 • [31]
System Energy Consumption	Total ≈300000joules ≈ 0.86KW/cycle 1 liter bath run for 15min cycle. • [37]	Total ≈300000joules ≈ 0.86KW/cycle 1 liter bath run for 15min cycle. • [37]

Total Cost Per Part	0.035-0.45 $ / • [31]	0.15-0.45 $ • [31]
System Cost	$10000 - $180000 • [31]	$10000 - $180000 • [31]
Emission Level	Low • [31]	Low • [31]

Table 8 - Ultrasonic Cleaning

Cleaning Types/Results	***Abrasive Blasting***	
Principle Types	*Dry Blasting• [15]*	*Wet Blasting• [15]*
Contamination Type	Rust / Oxidation / Carbon / Paint / Oil / Grease • [10]	Flash Rusting / Carbon / Paint / Oil / Grease / Dirt / Soluble Salt • [12] [74]
Contamination Level	Low / Medium / Heavy • [12]	Low / Medium / Heavy • [12]
Cleaning System Type	Mechanical / Compressed Pressure • [15]	Mechanical/Chemical - (Air/water/abrasive)/(water/abrasive) • [12] [74]
Processed Material Type	Soft Material (Aluminuium, Magnesium, Copper, Zinc and Beryllium,Plastic) , Hard Material (Steel, Iron) • [14] • [75]	Iron / Steel / Glass / Aluminum / Plastic / Copper / Brass / Wood • [12] [15][21]

Cleaning Chemicals	Sand, Slags (Coal, Copper and Nickel), Minerals (Garnet), Metalic (Iron,Steel), Glass, Ceramics, Sponge , Plastic Pellets, Natural Products (Rice hulls, Nut Shells), Natural Oxides (Silica) ,Carbon dioxide (Dry-Ice Blasting), Aluminium Oxide, • [11] • [12]	Air,Water(With low or high Ph and Temperature), Sand, Mild Alkali Cleaners (Spray - detergents, complexing agents, dilute acids or weak alkalis) - Two Step Process [1st. Caustic Soda (Strong Alkali Cleaners(rinsewater)] [2nd. Sulfuric or Nitric Acid (Rinse Water)] • [11]• [12] • [13]
Temperature	80- 100 psi air pressure / Mechanical Velocity ≈ 250 feet per second, Temperature (dry ice blasting): 20 to (-80) C • [15] • [19] • [76]	Ph = 5.7 - 10.1 Water Jetting (10000-30000psi) - High Pressure (5000-10000psi) Temperature: 20 - 90 C • [14] [15]
Cycle Time	2 - 30 Min • [10]	5-35Min - (300 Golf Balls - 5min) • [12] • [13]
Efficiency	Efficiency - Hard Material (Excellent), Soft Material (Good) • [11]	Efficiency - Hard Material (Excellent), Soft Material (Good) • [12]
System Type	Manual / Semi Automatic / Fully Automatic • [15]	Manual / Semi Automatic / Fully Automatic • [15]
Number of	1 or 2 • [10]	1 or 2 • [12]

Operator		
System Energy Consumption	1.14KW/KG blast (Pressure Blast) - 7.5KW/kg blast (Blast Whele Blasting System) • [77]	1.52KW/KG blast (Pressure Blast) • [77]
Total Cost Per Part	0.2 - 0.45 $ (Costs are $12 per hour for labor & $0.10 KWH)• [10]	0.35 - 14.3 $ • [12]
System Cost	$15000 - $55000• [10]	$17000 - $95000• [12]
Emission Level	High (Without Vacuum System), Recycling is possible • [75]	Low dust emission , Recycling is possible • [74]

Table 9 - Abrasive Blasting

Cleaning Types/Results	***Thermal Cleaning***	
Principle Types	*Dry Method • [48]*	*Wet Method (With Solvent Bath) • [48]*
Contamination Type	Cork Gasket / Resins / Paint / Plastics / Grease / Rust / Rubber Seal / • [44]	Cork Gasket / Resins / Paint / Plastics / Grease / Rust / Rubber Seal / Carbon • [45]
Contamination Level	Low / Medium • [44]	Low / Medium / Heavy • [45]
Cleaning System Type	Thermal • [48]	Thermal / Chemical • [48]
Processed Material Type	Iron / Steel / Aluminum / Zinc / Copper / • [44]	Iron / Steel / Aluminum / Zinc / Copper / • [44]

Cleaning Chemicals		Water, Calcium oxide, Aluminium oxide, Si2H6/H2 , AsH3/H2 , H2, H2SO4, H2O2, CH3COOH • [18] • [44] • [47] • [48]
Temperature	Temperature 30 to 1500 C • [46]	Temperature 50 to 950 C ,• [20] • [48]
Cycle Time	30min to 4hours • [44]	15 min to 1hour • [46]
Efficiency	Efficiency - Hard Material (Excellent), Soft Material (Good) • [44]	Efficiency - Hard Material (Excellent), Soft Material (Good) • [44]
System Type	Manual / Semi Automatic / Fully Automatic • [47]	Manual / Semi Automatic / Fully Automatic • [47]
Number of Operator	1 • [44]	1 • [45]
System Energy Consumption	0.4 - 6 KW / per cycle hour • [44]	0.3 - 6 KW/per cycle hour • [45]
Total Cost Per Part	0.08 - 0.44 $ • [44]	0.25 - 1.55 $ • [45]
System Cost	$8000 - $50000 • [44]	$12000 - $54000 • [44]
Emission Level	High ash emission • [48]	Low ash emission, high chemical • [48]

Table 10 - Thermal Cleaning

Cleaning Types/Results	*Laser Cleaning*	
Principle Types	*Dry Laser Cleaning• [30]*	*Steam Laser Cleaning• [30]*
Contamination Type	Sand /Graphite / Facecoat / Paint / Oils / Soils / Carbon / Paint / Grease / inorganic materials / organic contaminants /oxyhydroxide {any kind of surface contaminants} • [22] • [23]	Sand /Graphite / Facecoat / Paint / Oils / Soils / Carbon / Paint / Grease / inorganic materials / organic contaminants /oxyhydroxide {any kind of surface contaminants} • [22] • [23]
Contamination Level	Low/Medium • [78]	Low / Medium / High • [78]
Cleaning System Type	Mechanical • [30]	Chemical / Mechanical • [30]
Processed Material Type	Most of the type of materials • [22]	Most of the type of materials • [22]
Cleaning Chemicals		CO2, S2O2, Al203, SO2, Si3N4, polystyrene 10^{-2} to 10^{8} waves• [31] • [32]
Temperature	Wave Length 10^{-2} to 10^{8} Temperature 100-1000C • [78]	Wave Length 10^{-2} to 10^{8} Temperature 100-1000C • [78]
Cycle Time	1-2 min. • [22]	1-2 min. • [22]
Efficiency	Efficiency - (Good)• [22]	Efficiency - (Excellent) • [22]

System Type	Manual /Semi Automatic / Fully Automatic • [24]	Manual / Semi Automatic / Fully Automatic • [24]
Number of Worker	1 • [24]	1 • [24]
System Energy Consumption	120Kw - 800kw ≈ 2Kw - 12Kw per cycle • [24]	160Kw - 800Kw ≈ 3Kw - 12 Kw per cycle • [24]
Total Cost Per Part	≈ 2.5 $ • [24]	≈ 3$ • [24]
System Cost	$65000 - $430000 • [24]	$145000 - $430000 • [24]
Emission Level	Low dust emission • [22]	Low dust emission • [22]

Table 11 - Laser Cleaning

Cleaning Types/Results	***Molten Salt***	***Immersion Cleaning***	***Vibratory Cleaning***
Principle Types	*Molten Salt Bath Cleaning*	*Ionized /Deionized • [61]*	
Contamination Type	Sand / Scale / Graphite / Shell / Facecoat / Paint / Oils / Soils / Carbon / Paint / Grease / inorganic materials • [52] • [53]	Oils / Soils / Rust / Coolants / Grase / Carbon / Dirt / Gasket • [58]	Light Oil / Light grease /Rust / Paint / Dirt / Gasket / Carbon • [41]
Contamination Level	Medium • [53]	Low / Medium • [81]	Low / Medium•[41]

Cleaning System Type	Chemical and Thermal • [52]	Chemical / Mechanical • [81]	Chemical / Mechanical • [41]
Processed Material Type	Stainless Steel / Superalloys / Titanium / Refractory Metal / Aluminum / Zinc • [52] • [53]	Aluminum / Steel / Stainless Steel / Copper / magnesium / brass / zinc / bronze Refactory Metal • [24]	Aluminum / Steel / Stainless Steel / Copper / magnesium / brass / zinc / bronze / Refactory Metal • [41] • [42]
Cleaning Chemicals	Chlorides and Sulphates (Variety of them), Sodium Chloride, Hydrogen Sulphate, C3H7, C4H9, NO2-C6H4, C2H5, • [56] • [80]	Methyl Ethyl Ketone, Methyl Chloroform, and ODS-based solvents , Carbon Tetrachloride, Chloroform, Dichloromethane, Methyl ethyl ketone, Tetrachloroethylene, Methyl isobutyl ketone, 1,1,1-Trichloroethane , Toluene, Trichloroethylene, CO2, • [24] • [62]	**Media Types**; Ceramic, Resin-Bonded, Steel, Aluminum, Aluminum Oxide, Silicon Carbide Abrasive , Walnut Shell **Solvents**; Water, CO2, Enzymes , Trepenes, Organic Ester, Alkaline Detergent, • [41] • [42]

Temperature	50-950F - Low Ph on Process and High Ph on Rinse • [53] • [57]	60-90C (160 - 190 F) PH >6.5 <12-13 , 80-125psi air pressure • [24] • [60]	Velocity: dry conditions was 0.8±0.4 cm/s, and 0.6±0.4 cm/s in wet conditions Fre:0.1-280 Hz Force: 1 - 25 N • [43] • [82]
Cycle Time	10 to 30 min • [52]	2.5 - 6 mins • [61]	5 - 30 mins • [43]
Efficiency	Efficiency - Hard Material (Excellent), Soft Material (Good) • [56]	Efficiency - (Excellent) • [81]	Efficiency - (Good - Excellent) • [43]
System Type	Semi Automatic / Fully Automatic • [53]	Manual / Fully Automatic • [81]	Semi Automatic / Fully Automatic • [43]
Number of Operator	1 • [53]	1 • [81]	1 • [41]
System Energy Consumption	100000-150000Btu per hour ≈3 - 4.5 Kw/Per cycle hour • [57]	≈ 2 to 4 kw/hour • [62]	0.1 - 0.2 kw per 15min cycle • [41]
Total Cost Per Part	0.6 – 0.8 $ • [57]	0.06 - 0.13$ per part • [61]	0.04 - 0.07$ per part • [41]
System Cost	$9000 - $60000 • [57]	$5000 - $85000 • [24]	$3000 - $20000 • [41]

Emission Level	High smoke emission, high chemical • [56]	Low Toxicity and Non Hazardous • [58]	Low Chemical • [42] • [43]

Table 12 Molten Salt, Immersion and Vibratory Cleaning

The main cleaning processes mentioned and determined on the above chart with their different specifications, advantages and disadvantages. When system planning, total cost per part, system cost energy consumption and emission levels are significant factors. These factors are shown on the chart above but mainly remanufacturers look for the best cleaning result with these cleaning processes. The chart below shows the cleaning results with different types of cleaning, because for the remanufacturers the cleaning result is the more important than all other significant factors.

Cleaning methods	Lower limit of diameter of particles removed (μm)
Wiping	5
Brush scrubbing	0.5
Ultrasonic cleaning	0.5
Etching	0.5
High-pressure jet	0.2
Megasonic cleaning	0.2
Laser cleaning	0.1

Table 13 - Removal of Micro particles [27]

As shown on the figure, laser cleaning is more effective than most of the cleaning processes. Laser cleaning can be used for most contamination types and can result in a better surface quality at the end of the process. This figure also represents the smallest contamination thickness on the surface. To gain the highest efficiency level from laser cleaning, we can make the contamination thickness 0.1μm but the cleaning result depends on the too many factors. Therefore, instead of only using the literature reviews, mathematical model can give us more accurate results.

The following part of this thesis will explain all possible cleaning methods using a mathematical model with analysis of the significant factors.

3.1.2 Modeling of the Major Cleaning Processes

Cleaning process' effectiveness and cleanliness result can be determined through the evaluation of significant factors. Generally, models are designed with a 95% confidence level, which is considered when a model is chosen. Models can show differences depending on low significant factors, therefore before model is used, the entire factor in that environment has to be determined.

Models of cleaning processes are highly useful for system and plant design selection. Major cleaning models are shown on the bottom.

Abrasive Blasting Cleaning: The mechanical cleaning productivity model for abrasive blasting is shown below. Blast pressure, feed rate and other coefficients are used to determine this mathematical model, as summarized below.

Equation given below represents productivity/consumption as a function of pressure and feed rate [83].

$$Y = a + (b/P) + (c/F) + (d/P^2) + (e/ F^2) + f / (P * F) \qquad (1)$$

where,

Y = productivity in m^2/h or consumption in kg/m^2

P = blast pressure (PSI), applicable range: 80 to 120 PSI,

F = feed rate, applicable range: 3-5 turns of Schmidt valve 180-360 kg/h for rusted panels, 150-600 kg/h for painted panels,

a, b, c, d, e, and f are coefficients given in table [83].

Coefficients for productivity and consumption estimation

Surface type	Feed rate units	Parameter	*a*	*b*	*c*	*d*	*e*	*f*	R^2
Rusted panels	No. of turns	Productivity	−53.92	2653	445.44	−106 904	−778.11	−2935	0.74
		Consumption	77.27	−3061	−299.98	29 898	416.46	6376	0.59
	kg/h	Productivity	42.45	190.49	−11 661	12 710	1 175 713	−88 316	0.76
		Consumption	31.49	871.69	−7101	−211 194	−423 850	844 566	0.51
Painted panels	No. of turns	Productivity	−104.87	15 070	332.96	−798 827	−727.37	4026	0.99
		Consumption	425.48	−53 825	−754.96	2 699 557	1660	−16 101	0.51
	kg/h	Productivity	−48.52	13 269	−4361	−627 433	609 819	−117 302	0.80
		Consumption	428.85	−69 535	−16 619	3 250 010	704 637	582 089	0.67

Table 14 Coefficient for productivity and consumption estimation [83]

Laser Cleaning: When lasers focus on a point in the target surface, the thickness of the steel substrate is much larger than the thickness of the coating. As a result, a one-dimension half-infinity model is used. It considers the laser-induced transition in three stages, namely evaporation, melting, and solid heating [84].

Greek symbols

α	Absorption coefficient of laser induced plasma (cm^{-1})
δ	Skin depth (cm)
ε	Dielectric constant ($CV^{-1}\ m^{-1}$)
ε_0	Dielectric constant of vacuum ($CV^{-1}\ m^{-1}$)
η_0	DC resistivity (Ω m)
ν	Collision frequency (s^{-1})
ω	Laser frequency (s^{-1})
ω_p	Plasma frequency (s^{-1})
λ_p	Laser wavelength (μm)
τ	Laser pulse width (s)
ρ_l	Mass density of liquid ($g\ cm^{-3}$)
ρ_s	Mass density of solid ($g\ cm^{-3}$)

Equations of motion of solid–liquid and liquid–vapor boundaries

$$\frac{\delta}{\delta T}\mathrm{Zm(t)} = \frac{\mathrm{Vmcs(Tf-tm)}}{\mathrm{Lm}} \qquad \mathrm{Tf = T(Zm(t))} \tag{1}$$

$$\frac{\delta}{\delta T}\mathrm{Zm(t)} = \mathrm{Voexp}(-\frac{\mathrm{u}}{\mathrm{Tv}}) \qquad \mathrm{Tv = T(Zv(t))} \tag{2}$$

$$u=M_{Lv}/K_{B,} \tag{3}$$

Heating conditions:

$$\varrho(z,t) = I(t)(1-\alpha)\ 1-R\ /\ \delta\ \exp\ \{-(z-Z_v(t))/\delta \tag{4}$$

$$\delta = (2D\tau)^{1/2}\ ,\ D = Ks\ /\ p_s c_s \tag{5}$$

Boundary conditions:

$$Lm\frac{\delta}{\delta T}\mathrm{Zm(t)} = \mathrm{ks}\frac{\delta T}{\delta \mathrm{z}} - \mathrm{k1}\frac{\delta T}{\delta \mathrm{z}} \tag{6}$$

$$Lm\frac{\delta}{\delta T}\mathrm{Zm(t)} = \mathrm{k1}\frac{\delta}{\delta T} \tag{7}$$

Considering laser energy absorption and reflection by the target, we have

$$R = \frac{|n-1|^2}{|n+1|}\ ,\ n^2 = \varepsilon = e_r = i\varepsilon_i \tag{8}$$

According to model,

$$\varepsilon = 1 - \omega^2 \frac{1 - \frac{iv}{\omega}}{\omega^2 + v^2} \tag{9}$$

Where,

$$v = \varepsilon\omega^2\eta_0, \qquad {\omega^2}_p = \frac{e^2 n_e}{e_0 n_e}, \qquad \omega = \frac{2\pi c}{\lambda} \tag{10}$$

Using the known universal constants, the laser parameters, and the thermo-physical data listed in table [84].

Universal constants, laser parameters and material thermo-physical data[a]		
c	2.998×10^{8} m s^{-1}	[9]
e	1.602×10^{-9} C	[9]
k_B	1.054×10^{-34} J K^{-1}	[9]
m_e	9.108×10^{-31} kg	[9]
M	65.380 [c], 192.200 [s]	[10]
n_e	5.000×10^{28} m^{-3}	[9]
V_0	4.210×10^{3} m s^{-1}	[10]
V_m	7.000×10^{2} m s^{-1}	[10]
ρ_l	6.920 [c], 7.800 [s] g cm^{-3}	[10]
ρ_s	6.920 [c], 7.800 [s] g cm^{-3}	[10]
λ	1.064 μm	
τ	1.000×10^{-10} s	
ε_0	8.854×10^{-12} CV^{-1} m^{-1}	[9]
c_l	4.500 [c], 7.950 [s] $\times 10^{2}$ J kg^{-1} K^{-1}	[10]
c_s	3.940 [c], 4.560 [s] $\times 10^{2}$ J kg^{-1} K^{-1}	[10]
k_l	1.195×10^{2} [c], 36.000 [s] W m^{-1} K^{-1}	[10]
k_s	94.500 [c], 78.200 [s] W m^{-1} K^{-1}	[10]
L_m	7.200×10^{6} [c], 2.720×10^{5} [s] J kg^{-1}	[10]
L_v	1.319×10^{8} [c], 6.100×10^{6} [s] J kg^{-1}	[10]
T_m	692.650 [c], 1809.000 [s] K	[10]
T_v	1048.000 [c], 3133.000 [s] K	[10]

[a][c] and [s] express coating and substrate, respectively.

Table 15 Universal Constants, Laser Parameters and Material Thermo-Physical Data

Ultrasonic Cleaning: Since ultrasonic cleaning is the one of the most effective process for the cleaning of metal surfaces, the mathematical model of this cleaning type carries a great weight in this research. As explained in the cleaning methods literature review, this cleaning process has many steps and actions. Therefore, this model is more complicated and design has more factors than other cleaning processes.

Developed a correlation for the collapse pressure, P_C ($N\ m^{-2}$):

$$P_c = C_1(I)^a(r_0)^b(f)^c(\gamma)^d(r/r_0)^e \quad (11)$$

C_1 is a proportionality constant, I is the intensity of ultrasound ($W\ m^{-2}$), r_0 is the initial radius of a cluster (m), f is the frequency of ultrasound (Hz), r is the radius of cluster at collapse conditions (m), and γ is the fraction of energy transferred into the cluster, which is generated due to the collapse of the individual cavities on the outer boundary [32].

The instantaneous cluster wall velocity at the time of cluster collapse, SC ($m\ s^{-1}$), is:

$$Sc = [P_c/(p\beta(1-\beta))]^{1/2} \quad (12)$$

Where r is medium density and b is the void fraction in the cluster.

C_1 =0.0159
a = 0.33
b= - 0.134
c= - 0.042
d= 0.634
e= -2.969

Table 16 - Values of Constant and Exponents [32]

R_p is the radius of the particle, h is the liquid viscosity, v is the liquid velocity, and x is the coordinate perpendicular to the surface and W_A is the work of adhesion, defined as the sum of the surface energies of the two contacting materials minus the interfacial energy [32].

$$Ac = \eta x_0 Rp[P_c /(p\beta(1-\beta))]^{1/2} / (1.5W_A) \quad (13)$$

PC can again be estimated from first equation. The pressure exerted by the collapsing cavity cluster can also lead to cavitation erosion of the surface, with the onset and magnitude of surface erosion being primarily dependent on the material and on surface finish/quality [32].

$$\sigma_{EROS}=B.P_C \quad (14)$$

σ_{EROS} is the erosion stress associated with the sonic field and *B* is an ‘‘erosion susceptibility’’ constant for the specific immersed surface.

The constant, *B*, incorporates material and surface properties that influence cavitation erosion in an ultrasonic field.

$$B = 1 - [(Hm / H_D)(F_{G,min} / F_m)(1/(10Ra))] \quad (15)$$

where the subscript ‘‘m’’ represents the material of the surface being cleaned, the subscripts D and G refer to diamond and glass respectively, H denotes hardness, F stands for fragility, and Ra is expressed in mm. The definition of a fragility parameter and a table of fragility parameters for several metallic alloys and glasses are provided range from 44 for Zr-alloy glass formers to 238 for Al-alloy glass formers. The lowest measured value ($F_{G,min}$) is about 16 [32].

Such a net cleaning force exerted on the surface per unit area may then be written as:

$$\sigma_{Clean,Cav} = (\sigma_{tan,C} - \sigma_{EROS}) \quad (16)$$

$$\sigma_{Clean,Cav} = \eta/x_0[P_c /(p\beta(1-\beta))]^{1/2} - BP_C \quad (17)$$

This can be rewritten in the form:

$$\sigma_{Clean,Cav} \; AP_C^{1/2} - BP_C \tag{18}$$

Where:

$$A = (\eta/x_0) /[(p\beta(1-\beta))]^{1/2} \tag{19}$$

This leads to the interesting result that the net zero cleaning condition

$$P_c = C_1(I)^a(r_0)^b(f)^c(\gamma)^d(r/r_0)^e = (A/B)^2 \tag{20}$$

Pc,opt calculate with these given:

$$P_{c,opt} = [A/2B)]^2 \tag{21}$$

The corresponding optimal cavitation-based cleaning stress is given by:

$$\sigma_{Clean,Cav} = A^2/4B \tag{22}$$

Model can be designed for different type of processes and wavelength [32].

Vibratory Cleaning: Vibratory cleaning is one of the other types of mechanical cleaning. Mechanical settings are designed in consideration of all significant factors. Velocity, target area, media type and system speed are the significant factors used to determine the model below. This model is useful when determining the highest contact area cleaning efficiency with that setting. The average coverage Cn after n impacts at a given velocity, each producing the same fractional coverage Ar (impact area divided by target area), is given by

$$C_n = 1- (1-A_r)^n \tag{23}$$

n impacts occur, by,

$$f = \frac{n}{T} \tag{24}$$

Hence first equation,

$$T = \frac{\ln(1-Cn)}{f\,\ln(1-Ar)} \tag{25}$$

Ar (impact area divided by target area) and the diameter of the force sensor button (s)

$$Ar = c^2 / s^2 \tag{26}$$

c is the radius of the contact area,

$$c = R\left[\frac{1}{4}v^2 p_1 \pi^2\left(\frac{1-\mu_1^2}{\pi E_1} + \frac{1-\mu_2^2}{\pi E_2}\right)\right]^{1/5} \tag{27}$$

Here v and ρ1 are the impact velocity and density of the media of radius R, while E is Young's modulus and μ is the Poisson ratio of the media and target [43].

Immersion Cleaning: The immersion cleaning model is shown below. All significant factors are used to determine the immersion cleaning model. Particle energy needs to be determined for this model, which helps to determine the most suitable settings to attain the highest efficiency for this cleaning method.

Surface energy (γ_A) of the particle is calculated, using contact angle data and equation (28), (29) and (30).

$$\gamma_A = \gamma_{\text{Liq}} \,.\, \cos \Theta + \gamma_{\text{A-Liq}} \tag{28}$$

$$\gamma_A = \gamma_A^{\,d} + \gamma_A^{\,h} \tag{29}$$

$$\gamma_{\text{A-Liq}} = \gamma_A + \gamma_{Liq} - 2\left(\sqrt{\gamma_A^d + \gamma_{Liq}^d} + \sqrt{\gamma_A^h + \gamma_{Liq}^h}\right) \tag{30}$$

Here, γ_A and γ_{Liq} are surface free energy of particle trap wafers and liquid, respectively. $\gamma_{A\text{-}Liq}$ is interfacial free energy between particle trap wafer and liquid, γ_A d is dispersion energy of particle trap wafers, and γ_A h is dipole energy of particle trap wafers. The contact angles of immerse are measured and introduced in the above equations for the calculation of the surface free energies of the particle trap wafers. The surface free energies of particles ($\gamma_{particle}$) were also obtained by same procedure. Interfacial free energy between the particle trap wafers and the particles ($\gamma_{A\text{-}Liq}$) were obtained by equation (31). Work of adhesion between the particle trap wafers ($W_{A\text{-}Liq}$) and the particles were obtained by equation (5).

$$\gamma_{A\text{-}Particle} = \gamma_A + \gamma_{particle} - 2\left(\sqrt{\gamma_A^d + \gamma_{Liq}^d} + \sqrt{\gamma_A^h + \gamma_{Liq}^h}\right) \quad (31)$$

$$W_{A\text{-particle}} = \gamma_A + \gamma_{particle} - \gamma_{A\text{-}particle} \quad (32)$$

Interfacial free energy between a particle trap wafer and a particle ($\gamma_{A\text{-}particle}$) derived from the above equations has a relationship with desorption of a trapped particle. On the other hand, the work of adhesion between a particle trap wafer and a particle ($W_{A\text{-}particle}$) has a relationship with adsorption of a particle [85].

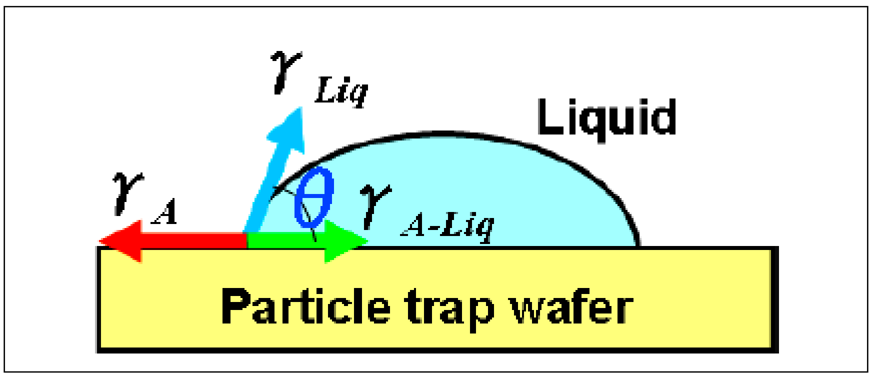


Figure 36 - Surface free energies of liquid [76]

Schematic figure of the surface free energies of liquid (γ_{Liq}), a particle trap wafer (γ_A) and a particle trap wafer -liquid interface ($\gamma_{A\text{-}Liq}$) [85].

After equations are used and the adsorption of the particle is calculated, system settings can be identified. Chemicals, system, nozzle speed and other settings can be designed based on these results.

Molten Salt Cleaning: University of Texas Pan American past graduate student research shows that effective research has been done regarding molten salt cleaning with sodium nitrate. This model will also be used in this research. In previous research, a cleaning model was designed using the main factors of molten salt cleaning, portion of sodium nitrate and temperature of the cleaning system. This model shown in the figure:

$$\text{Cleanliness} = 21.55 - 27.28*x - 0.02*y - 21.05*x^2 + 0.06xy + \varepsilon \quad (33)$$

Likewise, x stands for portion of sodium nitrate, y stands for temperature and ε represents error [86].

3.1.3 Modeling of the Contaminations

Major contaminant types are determined and modeled individually. This information is useful for finding general contamination thickness and determining the growth pattern of the individual or total contamination layer on the used workpiece surface. Previously created models are helpful when creating the cleaning or maintenance schedule design. When a suitable cleaning method is determined for the workpiece, the cleaning process is then designed. As mentioned in the literature review, each cleaning process has a given effectiveness on different types of contaminants. Thus, the main contaminant type is important for the cleaning method selection, while the thickness of the contaminant is important for the selection of the cleaning process cycle time, wavelengths, speed, media type and chemical.

After all of the above information is collected, the cycle time, energy consumption, and environmental impact of the system can be determined. These data points show the importance of the mathematical model for contamination growth and thickness. The mathematical growth models for major types of contaminants are shown and explained below.

Coating: Coating is the contamination type that can create significant effects on the metal service when seen in industry. Electrochemically active metals in different industries are often protected by coatings that can be broken down into three different types: organic, oxide and polymer coatings.

Organic coatings form a physical barrier between the metal and the surrounding atmosphere. These coatings provide a matrix in which other additives and/or inhibitors are solubilized or dispersed. The coating thickness ranges between 1–100 μm [87], which can make a difference in sensitive parts. Water, oxygen, and other aggressive species may penetrate the polymer coating causing the metal surface to become electrochemically active. When it becomes electrochemically active, the surface under the paint is defective where the base metal is exposed. This reaction must be detected, and the mathematical model must be considered based on contamination thickness. Because the effective difference between 1-100 μm is large on an engine surface, the model is incredibly important.

Layer growth between initial substances is due to continuous alternation of two consecutive steps for cases that combine reaction and diffusion. In the first step, diffusion of atoms of reacting substances across the bulk of the material takes place in opposite directions. Subsequently, chemical transformations take place on the outer layer, interfaced with the participation of diffusing atoms of one of the two components and the surface atoms of the other component.

According to reaction diffusion theory and the parabolic equation that was first introduced:

$$t = \frac{x^2}{2k_{1a1}} + \frac{x}{k_{0a1}} \tag{34}$$

Where t is the treatment time, x the coating thickness, k_{1Al} a physical constant [m^2/s] and k_{0Al} a chemical constant [m/s] [87].

Wear Debris: Depending on their chemical constitution, hydrocarbons from organic fuel, lubricated oil and fuel, and other types of organic and inorganic particles can be the cause for engine wear. The characteristics of wear on internal combustion engines have been studied, focusing on piston contamination types. The most common wear types are adhesion, scuffing, abrasion, corrosion and bore polish. These wear types are most frequently encountered on the cylinder and engine system [9]. Wear types are examined in the Piston Surface Structure and Contamination (2.2.1) part of this study.

As mentioned before, wear is a significant type of failure. It can cause problems on the workpiece surface, therefore the wear type's characteristic and growth rate is a significant factor for the determination of surface contamination thickness. The wear growth pattern mathematical model is shown below:

$$\delta=120KNSP_c^{m}H_b^{-m}(r-h_c)^{j}q^{t} \tag{35}$$

Where $K = k_1k_2k_3$. k1, k2, and k3 are respectively the coefficients of material surface properties, grinding particle properties and regional shape. N is the speed of a crankshaft, r/min, S is the travel of the piston. P_c means the average pressure for the piston ring surface. H_b is the hard degree of the parts. r is the equivalent radius curvature of abrasive particles, μm . h_c is the average film thickness. q is the weight concentration of lubricating oil and index m can be expressed as: $m = 3/4\beta$, $j = q/4\beta - 1/2$, $t=1 - 3/4\beta$. It is usually determined by the test, in which β is the surface roughness parameter. Generally desirable as $\beta=1.9$ [69].

Oxide Scale: Interactions between metals and oxides are key factors to determining the performance of oxide scale. Experimental and theoretical results from the literature regard the interactions between metals and oxides (TiO2, SrTiO3, Al2O3, MgO, SiO2, etc.). One central issue of concern in engineering metal/oxide interfaces is to understand and control the interactions, which consist of two fundamental aspects [88]:

a) Interfacial charge redistribution electronic interaction.

b) Interfacial atom transport chemical interaction.

The growth rate of a layer with thickness L follows from:

$$\frac{dL}{dt} = R_i J_i(L) \tag{36}$$

where *R*, is the volume of oxide formed per single action and $J_j(L)$ is the ionic flux for a film of thickness *L* [89].

Oxide scale is the one of the most common deficiencies on metal surfaces; the main reason is that oxygen atoms are chemically quite reactive and widely scattered in air and other compositions. Therefore, oxidation occurs more easily than other types of contamination. Some researchers consider oxidation in coating reactions, but an oxidation reaction can be much faster than other types of reactions. It is considered a burning reaction and this also proves that oxidation is a rapid reaction. According to this information, oxidation has to be considered different than coating.

Carbon Contamination: Carbon is another common ion type in nature and other compositions. Therefore, carbon contamination films exist and grow quicker than most of the other contamination types. Carbon ions' reaction speed is slower than oxygen ions, and cumulatively it is less than oxygen ions. As a result, carbon contamination growth speed is slower than oxidation but faster than other types of reactions. Because of this information, carbon contamination has to be considered as one of the significant contamination type because of its growth rate.

Most carbon contamination is based on energetic ions at a high density. A compressive stress is the main characteristic of C films; it has been proposed that the densification controls the C bonding. Thus, density and composition are crucial parameters to understand and control the growth mechanism of carbon films [90]. The heat of the surface and of the metal part is the main parameter for determining contamination growth rate. The following model is used for the determination of the contamination thickness on metal surfaces.

The thickness of the diffusion layer for most diffusion processes increases in proportion to the square root of the processing time and can be calculated using the equation:

$$d^2 = k \, . \, t \qquad (37)$$

where d is the thickness of the layer in m; k is the layer growth-rate constant in m^2/s and t is processing time in s [90].

The layer growth-rate constant depends on the processing temperature, since for heat-activated processes the exponential relationship of growth rate according to the Arrhenius equation is valid:

$$k = k_0 . e^{Q/RT} \qquad (38)$$

Where k_0 is the frequency factor in m2/s; Q is the activation energy of the process in J/mol; R is the gas constant in J/ mol K and T is the absolute temperature measured in K.

Salt:

It is known that for painted metals, the presence of hydrosoluble species within the layer of atmospheric corrosion products, mainly chlorides and sulphates, beneath the coating promotes osmotic blistering and under film metallic corrosion when the concentration of the soluble salts exceeds a critical level [92]. This kind of problem occurs very often in practice, when the metal surface painting is insufficient to cover and protect it from the effects of an aggressive atmosphere (marine, industrial, etc.).

Existing salt prior to coating, mainly chlorides and sulphates, is a cause for the failure of coatings [91]. As mentioned before, these salt types are mainly seen in marine and chemical industries. Also, engine parts of large ships, bots or water pipe systems can have difficulties with salt minerals during construction of the machine engine. Salt minerals mathematical model has been determined and is shown below.

R is the electrolyte capacity on metal surface of the salt layer

$$R = l_{sl} / \sigma p^{1.5} \quad (39)$$

where p is the porosity and l_{sl}, the salt layer thickness [91].

Dust: Dust is transmitted through the air, and generally includes sand, dirt, carbon dust, organic and inorganic particles. Therefore, it is impossible to standardize the main structure of dust because of vast differences in composition at different locations. Therefore, an Arizona University research team generated an acceptable design based on a generalization of the structure of the dust.

An extended accumulation of dusts may cause insulation resulting in thermal failure or circuit failure. Some hard dust like Arizona Test Dust (ATD) which is used in labs for research can even cause wear failure. The artificial dust - ATD comprises of 68-76% SiO_2, 10-15% Al_2O_3 and other metal oxides [93].

Component	Weight %
SiO_2	68–76
Al_2O_3	10–15
Fe_2O_3	2–5
CaO	2–5
K_2O	2–5
Na_2O	2–4
MgO	1–2
TiO_2	0.5–1

Table 17 - Arizona Test Dust Components [93]

As shown on the graph, chemically complicated structures and a high range of difference in compound weights make it impossible to create a direct model for dust contamination layer thickness.

Contamination Growth Model: Generally the models mentioned above for dust, carbon, oxide scale, wear debris, and coating, are the most common types of contaminants on the surface of engines and industrial metal parts.

Different types of mixed contamination can be particularly harmful. Mixed contamination poses a particular challenge because of the combination of different types of hazards and potential exposures. Mixed contamination comprises approximately 0.4 to 2% of all contamination [94]. Mixed contamination also differs by the location of the remanufactured product. After contamination thickness is generated for the workpiece, mixed contamination difference is considered and system design can be based on the last result.

As mentioned on the contamination model, all significant factors were considered when models were designed. Workpiece specifications are critical for the contamination thickness and structure assumption. After assumptions are made, the cleaning process design can be more accurate and this information also be used in the cleaning models which are explained in the next section.

3.2 Cleaning Process Selection, Modeling and Planning

3.2.1 Cleaning Process Selection

After the evaluation and models are created, the next step is the selection of the major cleaning processes based on the types and thickness of contaminants, types of part material, part geometry, and user input related to design objectives including total cost, energy consumption, environmental impact and processing time. Received parts condition was considered as it is reusable. Selected main process may require certain pre-processes before the conduction of the main process. It might also need post-processes for the purpose of rinsing and polishing. These pre or post processes will be selected together with the main process so that the whole process planning can be achieved.

The overall planning procedure is illustrated in figure

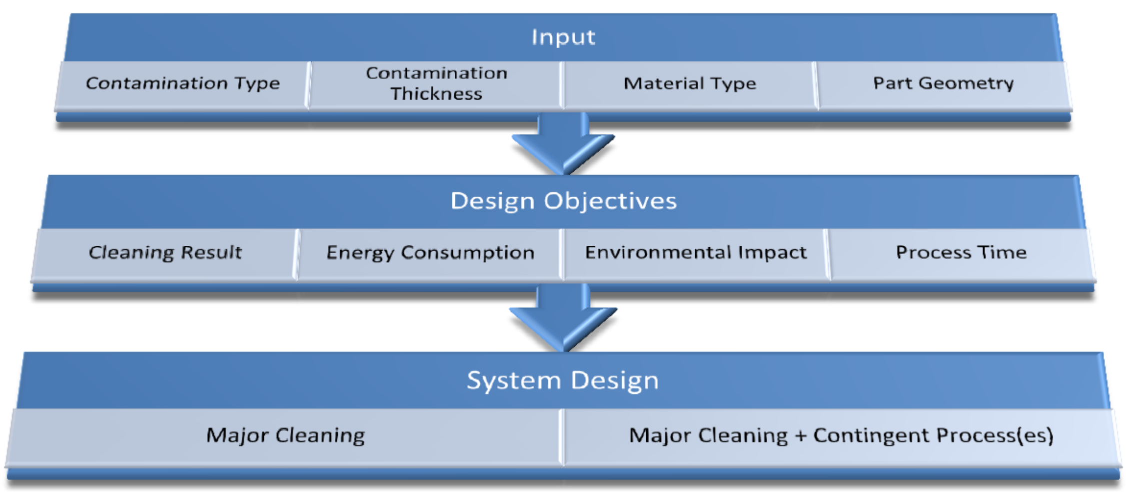


Figure 37 - System Design Flow Chart

Cleaning in preparation for remanufacturing is a complex process, which is influenced by system design, machine settings, user input and condition of the parts to be cleaned. The optimal settings for cleaning parameters should also be determined for each workpiece, based on specific part conditions and the contamination identified. Due to lack of quantitative models, system input ranges are created to be as wide as possible so that they can be applied to a wide variety of part conditions. Previous sections of this study showed the importance of making use of the most appropriate settings and correct design on the cleaning line to reduce energy costs and environmental impact and increase cleaning efficiency. To clean metal parts, machine behavior is registered for different machine settings and line designs.

Selecting system parameters must start with the determination of the correct inputs. The inputs themselves are created by considering the specifications of used parts. Workpiece material and contamination specifications are weighed most heavily in the creation of the cleaning process line. Part material, size, geometry, contamination thickness, type and chemical components all help to determine the major cleaning process. After this determination, the system is designed using the given inputs and contamination thickness is found. Previous research maintains that if the sizes of both ferrous and silica particles are within 10 microns, the wear condition in this case is low. If the size of silica particles is up to 20 microns, the wear condition is medium. And the wear would become abrasive wear when the silica particles are close to 40 or 50 microns [95]. Cleaning systems can be designed for different thicknesses. Thickness is considered one of the significant factors for process design. Test and experimental results also help to determine contamination type; organic, inorganic and/or organic inorganic mixture. If part has small or medium size of holes on it, part should be considered as a complex geometrical part. Processed material can be categorized as hard metal, soft metal or other types of alloys. This information has to put together and as mentioned and summarized on Table 10, 11 and 12.

After the system is designed based on part and contamination features, the system can be improved depending on customer expectations for cleanliness, time, cost and environmental impact. Customer cleaning expectations can push the designer to make changes. These requests may alter the process cost and time, but may also improve the result. These kinds of needs from the customer make the designer put contingent cleaning steps in the cleaning processes. Some of the major cleaning processes may even require a contingent process.

Remanufacturing cleaning system cleaning processes are studied under two different groups, major processes and contingent processes. Contingent processes can be applied to increase the result of cleaning, and it can be applied either before or after the major process. Categorization of the major and contingent processes is below:

Major Cleaning Processes: Laser Cleaning, Abrasive Blasting Cleaning, Ultrasonic Cleaning, Vibratory, Molten Salt Cleaning, Immersion Cleaning, and Thermal Cleaning.

Contingent Cleaning Processes: Spray Wash, Ultrasonic Cleaning, Vibratory, Thermal Cleaning, Brush Cleaning, Water Rinse and etc.

The table shown below is covering all major and contingent processes to determine correct cleaning type for the remanufacturers.

Cleaning Type:	Contamination Thickness	Contamination Type:	Material Type:	Geometry:
Laser Cleaning	Low	Organic	Hard Metal	Simple
	Medium	Inorganic	Other	
	High	Organic + Mix		
		Organic + Mix + Inorganic		
Abrasive Blasting Cleaning	Low	Organic	Soft Metal	Simple
	Medium	Inorganic	Hard Metal	
	High	Organic + Mix	Other	
		Organic + Mix + Inorganic		
Ultrasonic Cleaning (Individual and Contingent)	Low	Inorganic	Soft Metal	Complex
	Medium		Hard Metal	Simple
	High		Other	
Molten Salt Cleaning	Low	Organic	Hard Metal	Complex
	Medium	Inorganic		Simple
	High	Organic + Mix		
		Organic + Mix + Inorganic		
Immersion Cleaning	Low	Organic	Soft Metal	Complex
	Medium		Hard Metal	Simple
	High		Other	
Thermal Cleaning (Individual and Contingent)	Low	Organic	Hard Metal	Complex
	Medium			Simple
	High			
Vibratory Cleaning (Individual and Contingent)	Low	Organic	Hard Metal	Simple
	Medium	Inorganic		
	High	Organic + Mix		
		Organic + Mix + Inorganic		
Spray Wash	Low	Organic	Soft Metal	Complex
(Contingent)		Inorganic	Hard Metal	Simple
			Other	

Table 18 - Cleaning Processes Applicable Contamination Thickness and Type and Material Type and Geometry

As shown in the graph above, not every type of contamination can be cleaned with the same type of cleaning process. Material type and part geometries are significant factors for process selection.

3.2.2 Process Modeling and Planning

This table is useful for major cleaning process selection. After major cleaning process is selected, contingent process selection is done by using figure which is below.

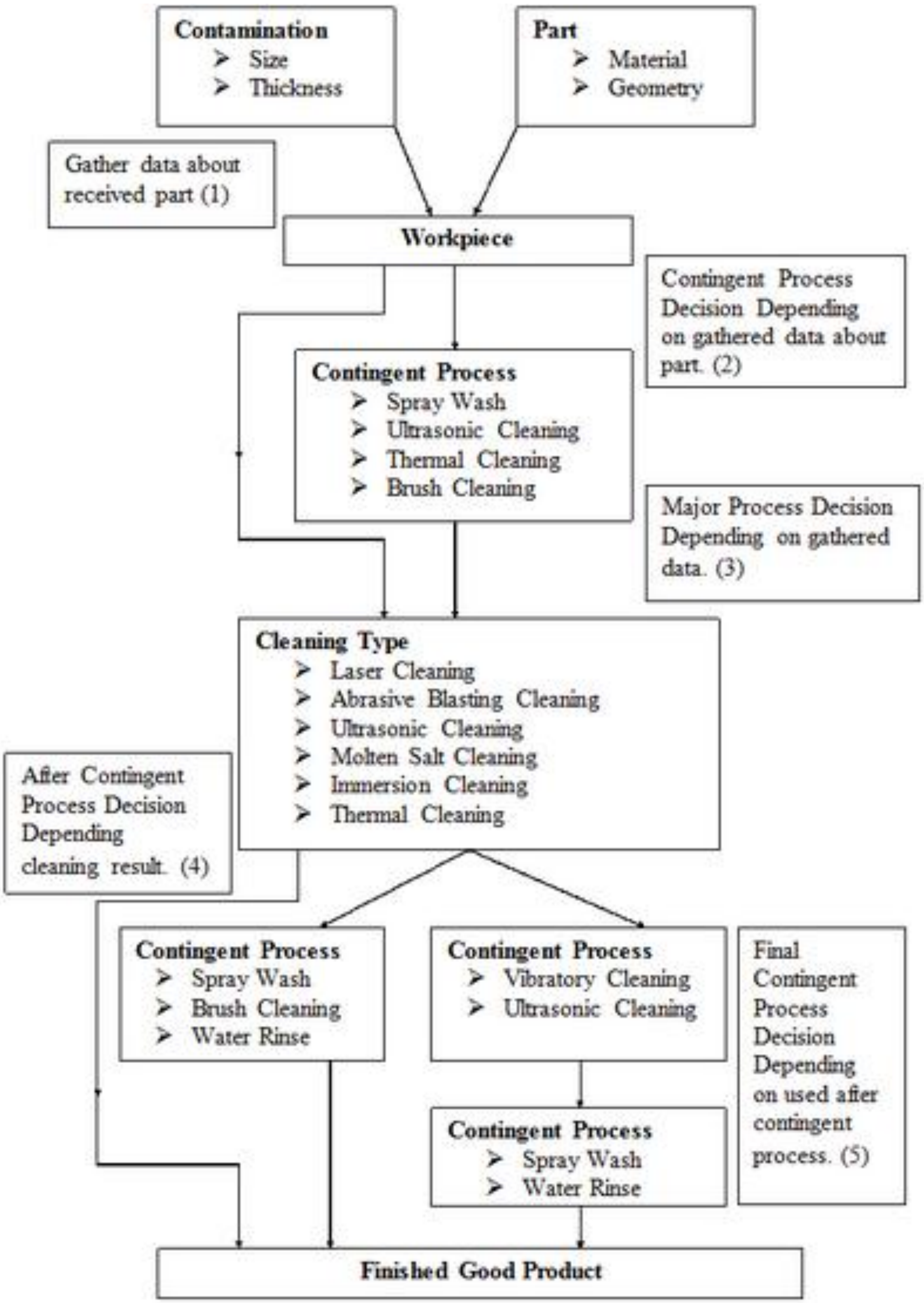


Figure 38 - Process Planning

Contamination thickness and part geometry are the most significant factors for energy consumption determination and process time. Contamination type and thickness help to determine environmental impact. The figure shows that each cleaning process works differently depending on contamination type, contamination thickness, part material and part geometry. The flow of each cleaning process is also shown below.

Laser Cleaning: Laser cleaning system design selection is shown below. The system is separated based on contamination thickness and contingent process applications are designed. Spray cleaning is the only contingent process that is used with laser cleaning, and it is applied before, after or before and after the process.

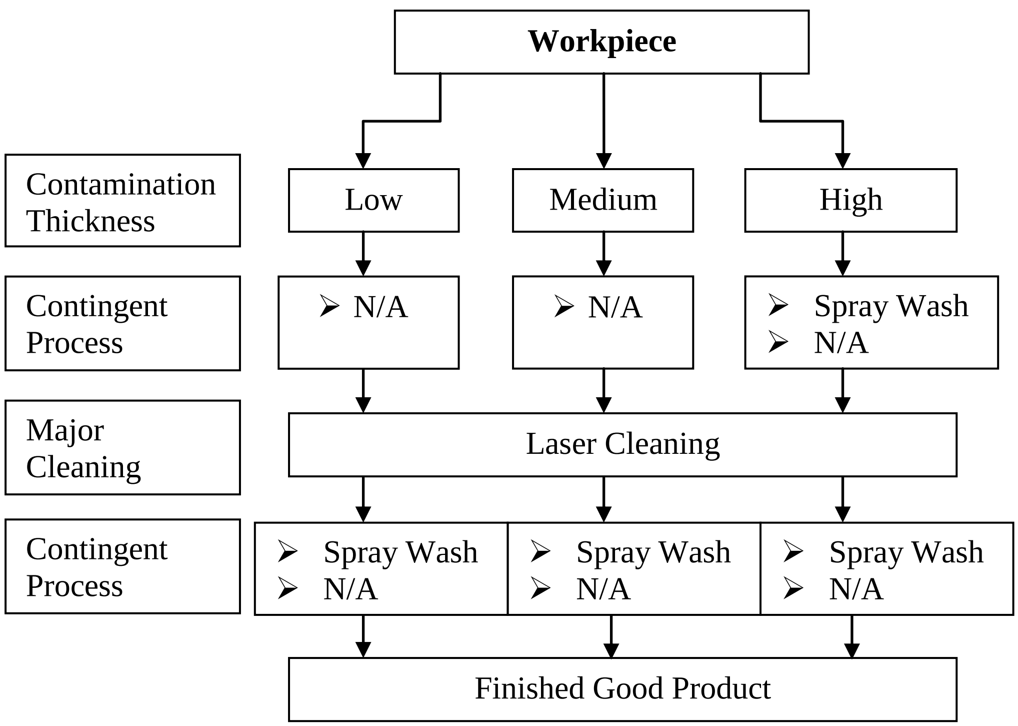


Figure 39 - Laser Cleaning Process Design

Abrasive Blasting Cleaning: Abrasive blasting cleaning process flow chart is shown below. For this process, spray wash and ultrasonic contingent cleaning processes can be applied. Ultrasonic pre cleaning process is applied before abrasive blasting cleaning started.

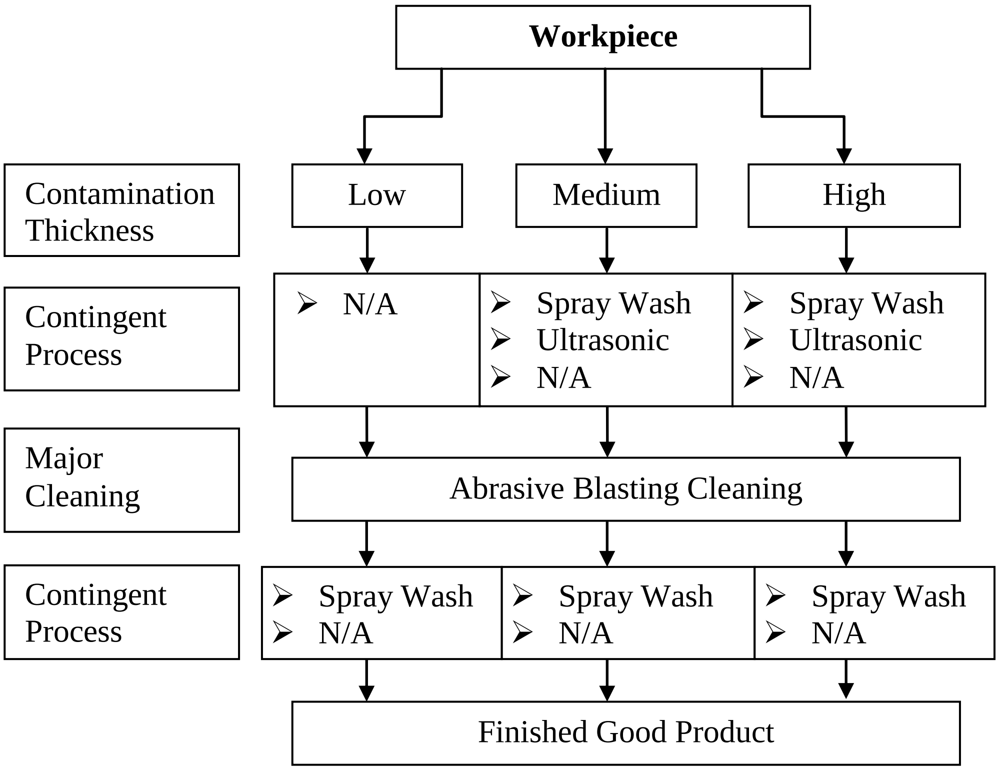


Figure 40 - Abrasive Blasting Cleaning Process Design

Molten Salt Cleaning: As mentioned before, the molten salt cleaning process uses strong chemicals. Cleaning results are always high with correct chemical selection for contamination. Therefore, the system does not require strong contingent processes; only a spray wash process is applied if needed. The only exception is if contamination is really thick, spray wash can be applied before major process to make contamination loose and increase the system efficiency.

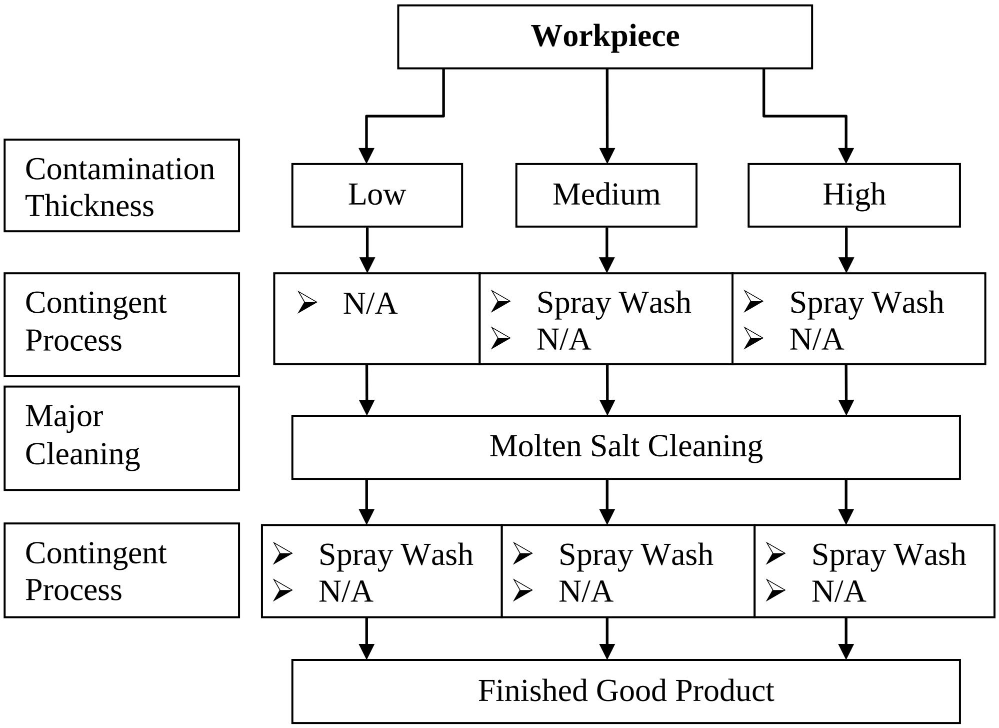


Figure 41 - Molten Salt Cleaning Process Design

Immersion Cleaning: Immersion cleaning is one of the most useful cleaning processes and only a spray wash contingent process can be integrated to the system. For immersion cleaning, contingent processes can be applied before, after, or before and after the process depending on contamination thickness.

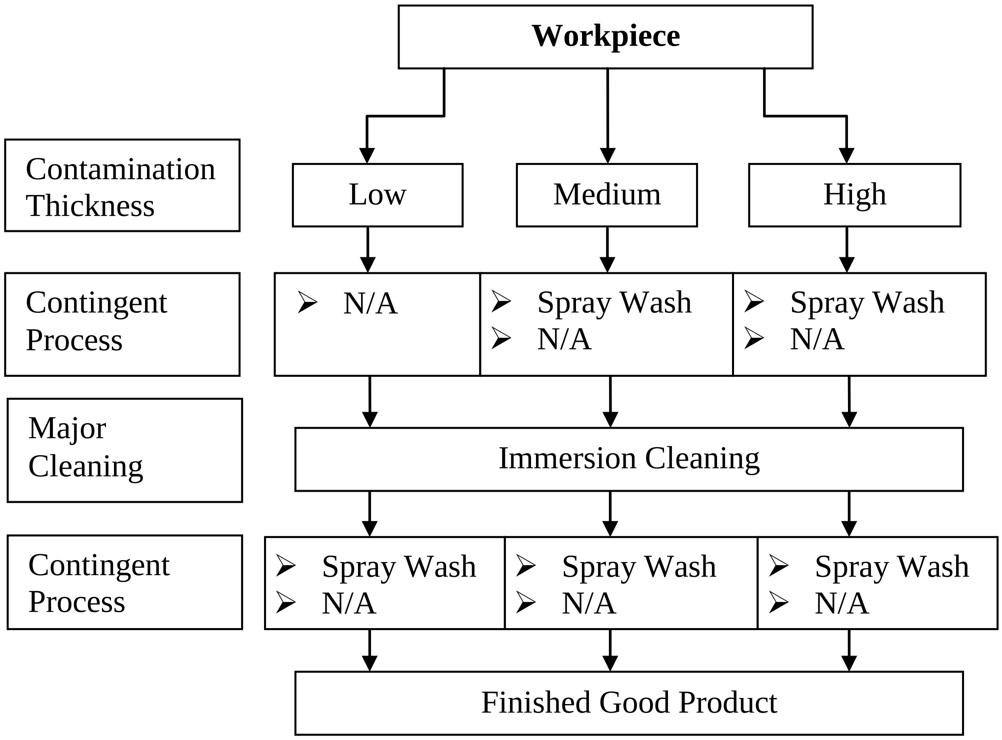


Figure 42 - Immersion Cleaning Process Design

Thermal Cleaning: Thermal cleaning is used as both a major and contingent process. This shows that the system by itself is not really effective. Thus, thermal cleaning process is always used with a contingent process. As shown in the figure below, before or after spray wash can be integrated to thermal cleaning process.

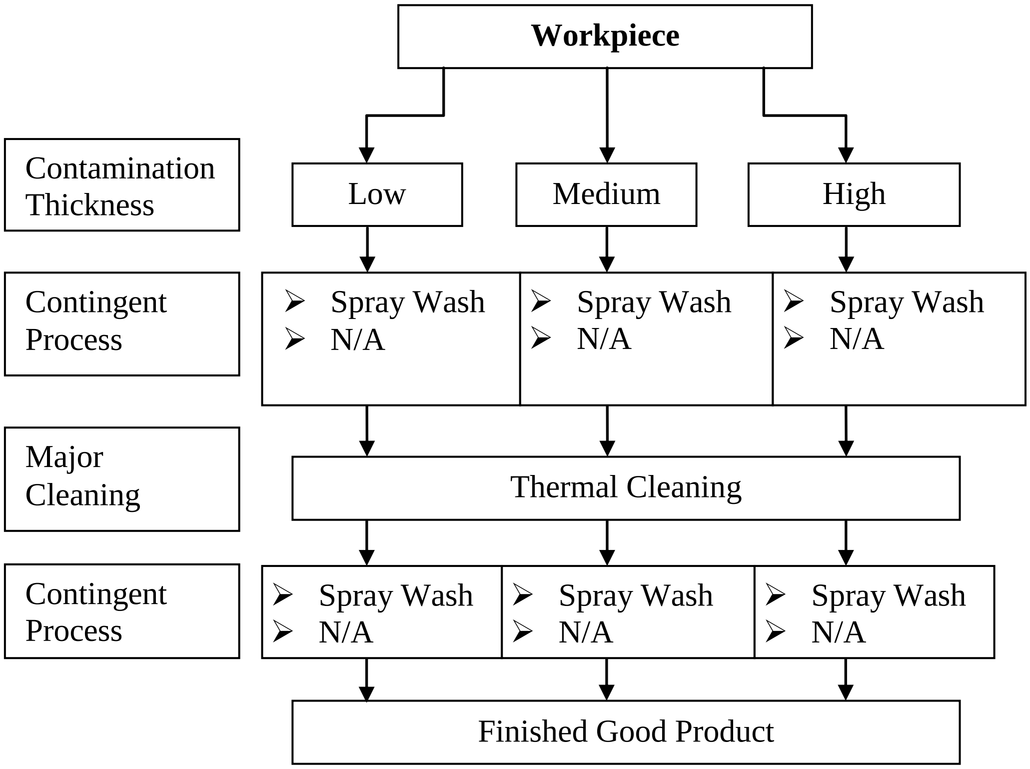


Figure 43 - Thermal Cleaning Process Design

Ultrasonic Cleaning: Ultrasonic cleaning is also used as a contingent process and major cleaning process. System by itself is a very strong process, but with different ultrasound waves, ultrasonic cleaning can be integrated as a contingent process to other processes. Other types of contingent processes can also be integrated with the ultrasonic cleaning process, like spray wash, thermal cleaning, or vibratory cleaning. All possible contingent processes and process flow with integrated contingent processes are shown in the figure below.

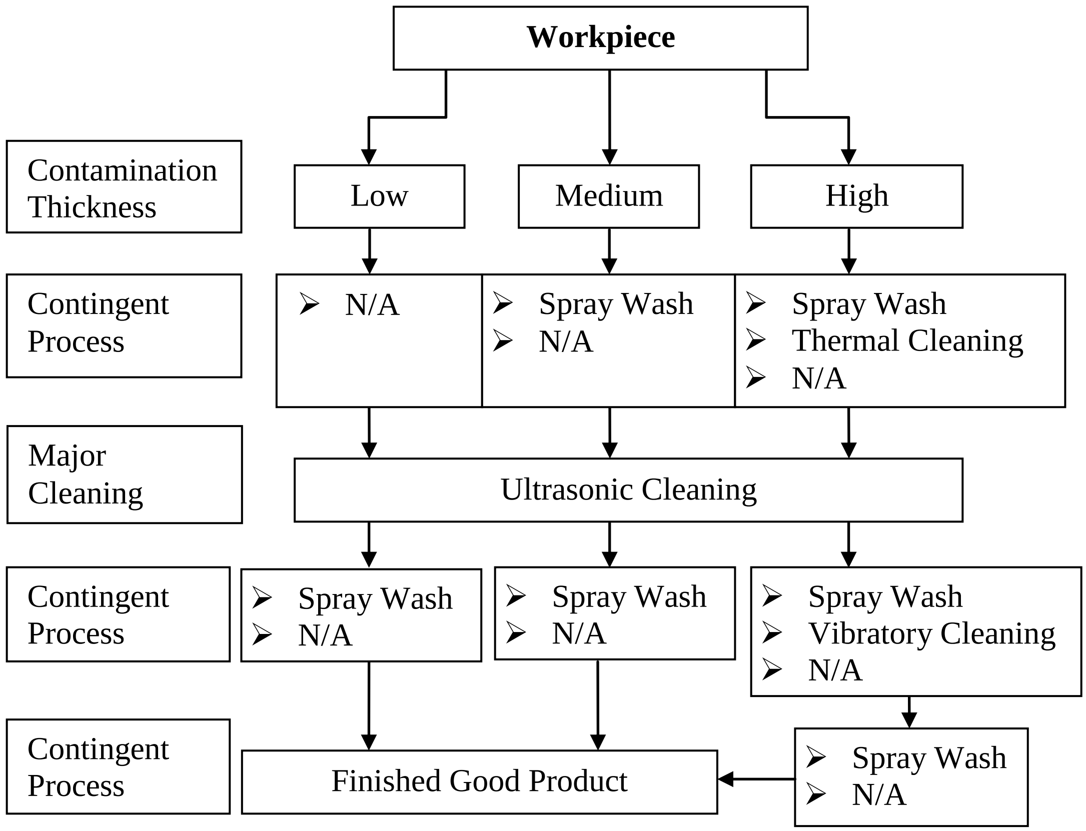


Figure 44 - Ultrasonic Cleaning Process Design

Using previous research, literature reviews and data, each cleaning process schema design is shown below with contingent process order. Contingent processes are not required for the system but it makes the cleaning result better and system can work with high variety of contamination types and thicknesses. Optimization is achieved using correct settings of major and contingent process selection.

If process selection and contingent process design and optimization have to explain by algorithm;

	Determine the input
	Contamination level
	Contamination type
	Part material
	Part geometry
	Set the software using the input,
	Software generates a major cleaning process,
	Software generates all possible cleaning processes and contingent processes
	Initialize the cleaning results
	Initialize the result of environmental impact
	energy consumption
	processing time
	system cost
	Initialize the inference results
	Find good fit processes to customer needs
	If it doesn’t match with customer needs, re run the software
	Input relevant information determination,
	Get the determined results from software environmental impact
	energy consumption,
	processing time
	system cost
	cleanliness
	System Decision

Table 19 - Process Algorithm

After cleaning process selection is complete, contingent processes can be determined using decision-making trees. Contingent process selection is also based on cleaning result needed and assumed energy consumption. The software has been designed for each process’ cleaning result and with additional contingent processes. Estimated energy consumption and environmental impact are the outputs generated by the software.

CHAPTER IV

SOFTWARE DEVELOPMENT AND DEMONSTRATION

4.1 Software Development

To assist process selection and process planning discussed, a simple software package was developed based on the methodology presented in chapter three.

The main goal of the software is to generate a list of options and assist user to choose the one that meets specific remanufacturing needs. First, user is asked to input the main characteristics of the workpiece to be cleaned and the contamination composition. The software then generates all possible cleaning processes based on user input. Also, with each cleaning method, the software automatically identifies the required pre and post contingent processes. Additionally, the software can generate an output for total energy consumption, processing time, system cost, environmental impact, and cleaning results for any selected processes. These outputs are based on the range of performance found in literature.Thickness is generated as low, medium and high, and low thickness is 1 to 5μm , medium 5 to 10μm and high contamination thickness is over 10μ. Software has an input section, which was created to make it more user-friendly for customers. The model created in the previous section is not used in this study, but ranges can be replaced with the model in future research. Software interface is shown in Figure 44,

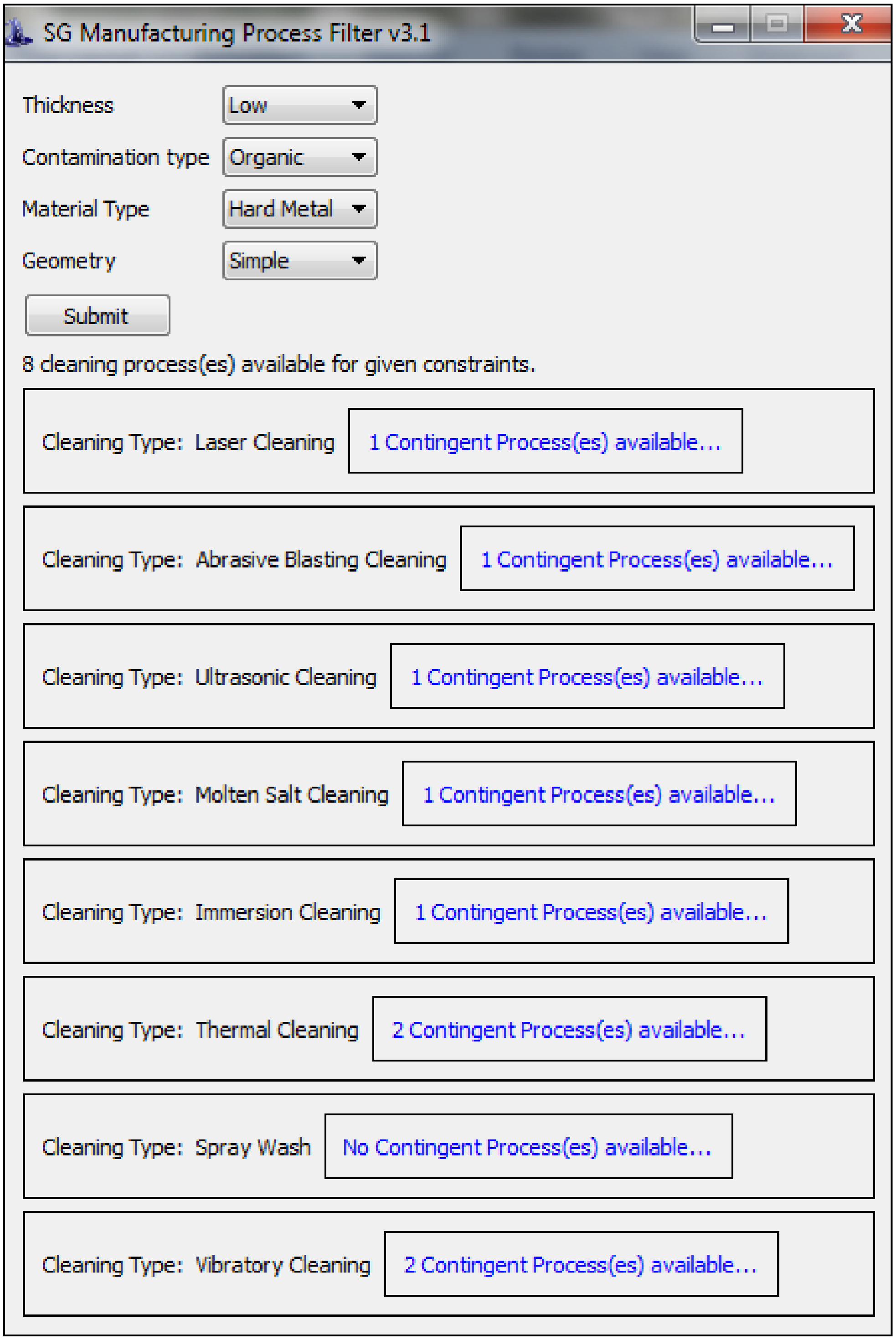


Figure 45 - Software Interface

As seen on the graph, software generates all the possible cleaning methods with recommended contingent processes. Possible cleaning processes can be compared with the output of the software. As illustrated, contingent processes are also included in the output. In some special occasions, many contingent processes can be available. Fort this case, the software provides a summary of cleanness, total system cost, total energy consumption and total process time, which give the customer a chance to compare all possible contingent processes. For example, for certain contingent processes, cleaning result may be improved. However, the customer may have limitations on energy usage, so software gives the user the chance to choose the processes that best fit their need. Using one specific example helps illustrate the decision-making process. If the customer has a part with high contaminant thickness, a mixture of organic and inorganic, and a simple shape of hard metal, the part is to be cleaned as shown below. Three different contingent processes are possible. In this case, abrasive blasting is one possible main process, and spray wash and vibratory cleaning can be applied in different variations. These different variations can give us different cleaning and process results. As shown in the figure, with the software it is really easy to compare the differences.

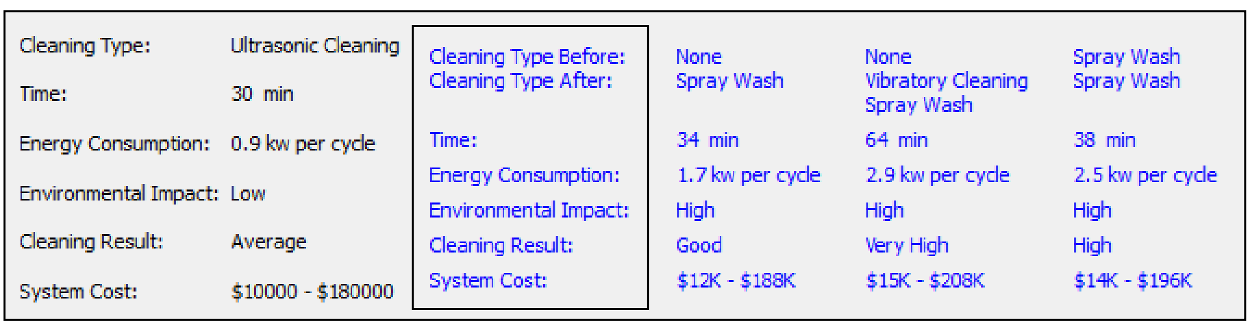


Figure 46 - Software Result Interface

To better demonstrate the research methodology, a demonstration is conducted using piston as the part to be cleaned. Currently, engine pistons are made of gray cast iron or steel, and the piston is chromium plated. The piston has to be made of strong and reliable material.

4.2 Piston Demonstration

They are a variety of significant factors to be considered when selecting a cleaning method for engine pistons. As seen in the figure below, piston has a complex geometric shape. The fact that a single piston contains a pin bore, piston ring, oil ring, pressure pin oiling channel, and other grooves must be considered when selecting a cleaning process. The chosen cleaning system has to be an ideal fit for cleaning in complex shape parts. When system design selection is made with the software, part geometry selection must be complex for piston cleaning process design.

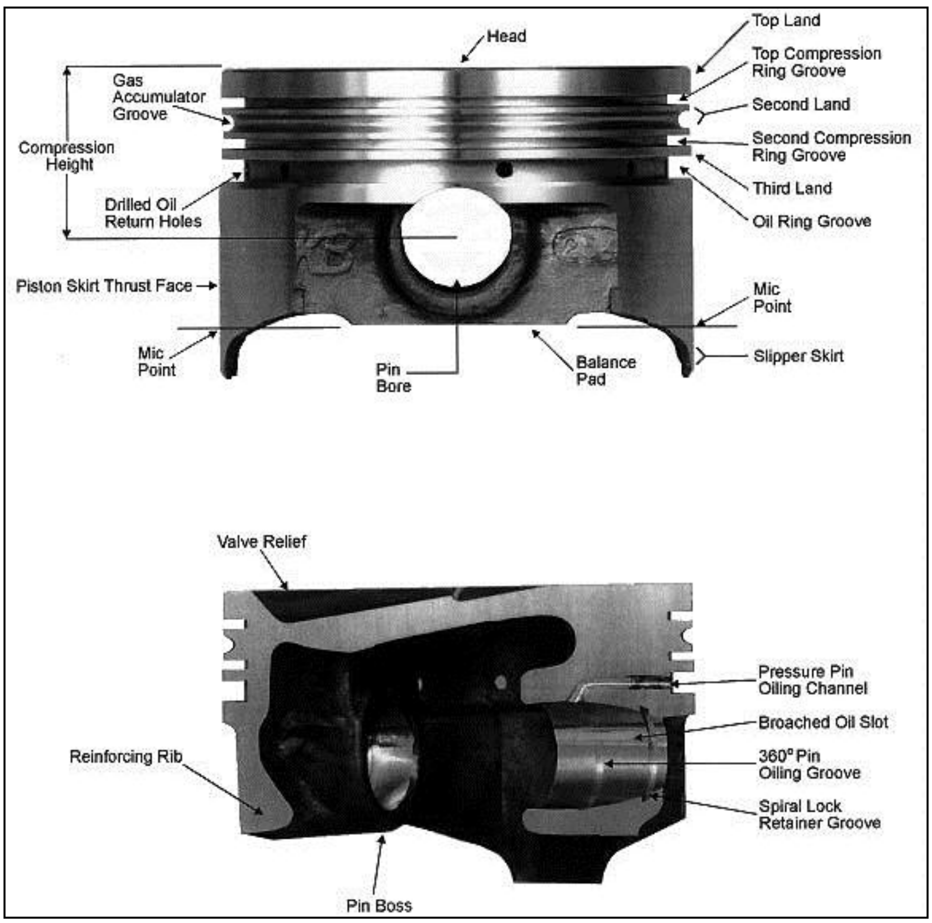


Figure 47 - Piston Cross Sections

Another significant factor in cleaning process selection is the contamination type. As previous research shows, carbon solid powder, oil, and grease is found on the piston surface during contamination analysis. Hydrocarbons also create a wear on the surface. The particles that cause this wear come from organic fuel and are called soot. Lubricated oil and fuel, depending on their chemical constitution, can be the causes for engine soot wear.

Based on the level of contamination on the piston, the type of contamination can be determined. If the contamination level is low, only organic contamination is present. If the level is average, it is either organic contamination only or organic plus a mix of organic and inorganic contaminants. If a high level contamination is present, it is organic, organic and mix, or organic, mix and inorganic type of contamination. Also as mentioned on chapter 2.2.2, engine parts are designed with hard metals.

The best possible design parameter is a high level of organic, inorganic and organic-inorganic mixture contamination. Just as with the scenario above, options for possible cleaning solutions become limited as contamination levels increase and the contamination chemistry is more complicated. Most suitable processes are shown with the following graph and also applicable contingent processes are shown with the software. The piston features used for this demonstration are shown below:

- Contamination Level: High
- Contamination Type: Organic + Inorganic + Organic and Inorganic Mixture
- Material Type: Hard Metal
- Part Geometry: Complex

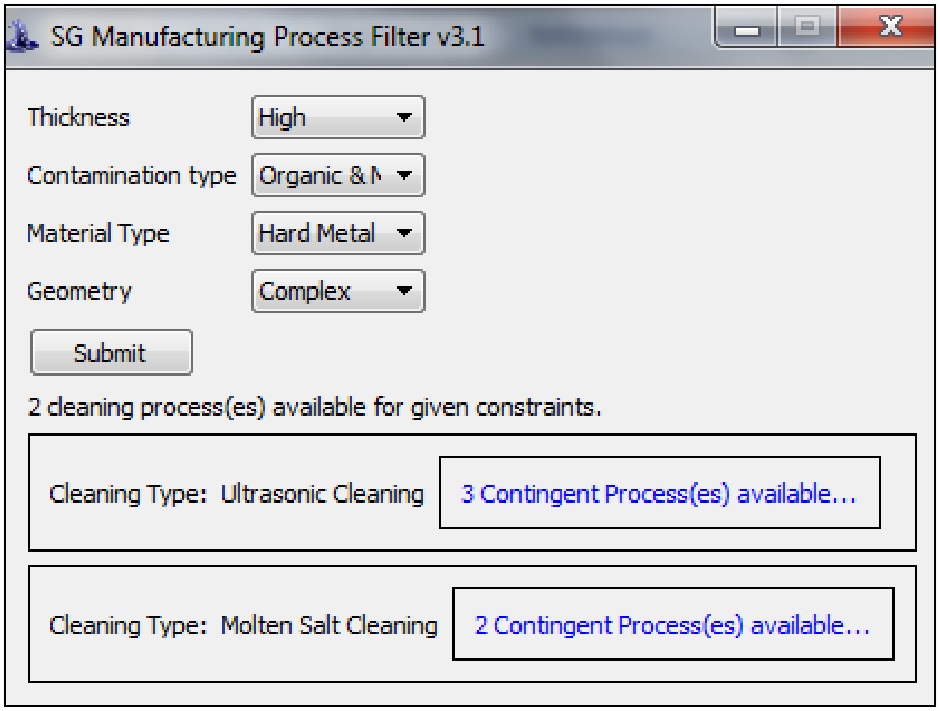


Figure 48 - Software Interface with Piston Input

Software generated two different processes and contingent processes are available for these cleaning processes. These options are discussed and shown below. Each cleaning process result is shown with and without possible contingent processes.

Ultrasonic Cleaning: When software is set for the piston features given above, one of the suitable processes generated is ultrasonic cleaning. System process parameters were generated with software to give user chance to compare all parameters.

Cleaning Type:	Ultrasonic Cleaning
Time:	30 min
Energy Consumption:	0.9 kw per cycle
Environmental Impact:	Low
Cleaning Result:	Average
System Cost:	$10000 - $180000

Cleaning Type Before: Cleaning Type After:	None Spray Wash	None Vibratory Cleaning Spray Wash	Spray Wash Spray Wash
Time:	34 min	64 min	38 min
Energy Consumption:	1.7 kw per cycle	2.9 kw per cycle	2.5 kw per cycle
Environmental Impact:	High	High	High
Cleaning Result:	Good	Very High	High
System Cost:	$12K - $188K	$15K - $208K	$14K - $196K

Figure 49 - Ultrasonic Cleaning Results on Piston Input

The figure below shows the comparison of all these possible methods. Red highlighted boxes show the advantages of that process over other possible process. Data shows that without pre and post process energy consumption, process time, environmental impact and total cost are really low but cleaning result is not as good as with contingent processes. If vibratory cleaning and spray wash cleaning were added after ultrasonic cleaning, system cleaning result reaches its highest level. Depending on customer objectives, a pre and/or post spray wash cleaning can be applied to improve the cleaning result. As explained in previous section of this study, vibratory cleaning is also used as a main process. The combination of two main processes create a highly satisfying cleaning result but system cost and process time are comparably higher than other possible options.

	Without Additional Processes	After: Spray Wash	After:Vibratory Cleaning + Spray Wash	Before: Spray Wash After: Spray Wash
Total Process Time	30min	34min	64min	38min
Energy Consumption	0.9kw	1.7kw	2.9kw	2.5kw
Environmental Impact	Low	High	High	High
Cleaning Result	Average	Good	Very High	High
Total System Cost	$10.000 - $180.000	$12.000 - $188.000	$15.000 - $208.000	$14.000 - $196.000

Figure 50 - Piston Cleaning - Ultrasonic Cleaning Software Results Comparison

Ultrasonic cleaning result was determined with software and is shown in the figure, using the cleaning flow found in previous research. In the figure below, red shapes describe the main process steps and blue shapes describe the possible contingent processes. With the flow chart, system steps can be known and as mentioned before contingent processes are optional depending on customer objectives. This figure helps the customer explore how to apply their cleaning process and contingent processes, with cleaning process results are shown above. The pre cleaning is used to loosen the strong contaminants and improve main process effectiveness. Vibratory cleaning and spray wash cleaning can be applied as a post cleaning process to create a finish on piston surface.

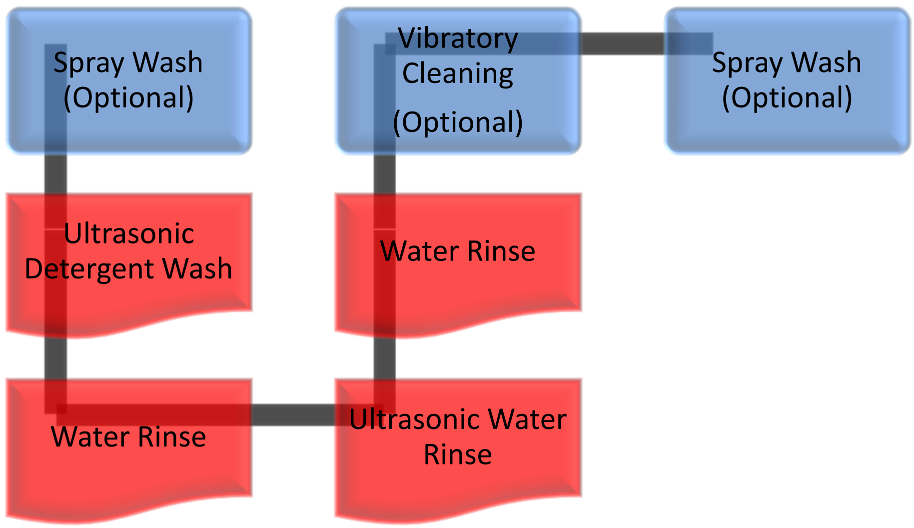


Figure 51 - Ultrasonic Cleaning Flow Chart

Molten Salt Cleaning: The figure shows all applicable pre and post cleaning processes when molten salt cleaning is applied to the piston part. So with the result of each process, user can compare and make the selection based on their need.

Cleaning Type:	Molten Salt Cleaning
Time:	30 min
Energy Consumption:	4.5 kw per cycle
Environmental Impact:	High
Cleaning Result:	Average
System Cost:	$9000 - $60000

Cleaning Type Before: Cleaning Type After:	None Spray Wash	Spray Wash Spray Wash
Time:	34 min	38 min
Energy Consumption:	5.3 kw per cycle	6.1 kw per cycle
Environmental Impact:	High	High
Cleaning Result:	High	Very High
System Cost:	$11K - $68K	$13K - $76K

Figure 52 - Molten Salt Cleaning Results on Piston Input

Based on the software's results determination, the table below was created. In piston cleaning case, one of the possible cleaning methods is molten salt cleaning. The red part of the table shows the positive advantages of each process. Without pre or post process system, cleaning process time is shorter, energy consumption is lower and total cost is better but cleaning result is lower than other cleaning. If spray wash was applied before or after main process, system cleaning result can reach the highest level. All the possible methods have high environmental impact.

	Without Additional Processes	After: Spray Wash	Before: Spray Wash After: Spray Wash
Total Process Time	30min	34min	38min
Energy Consumption	4.5kw	5.3kw	6.1kw
Environmental Impact	High	High	High
Cleaning Result	Average	Good	Very High
Total System Cost	$10.000 - $180.000	$12.000 - $188.000	$14.000 - $196.000

Figure 53 - Piston Cleaning - Molten Salt Cleaning Software Results Comparison

For engine piston cleaning, another useful cleaning process is molten salt cleaning process. The process flow is shown below. Based on previous research, the major cleaning process flow chart is shown with the red figures, and blue figures indicate the contingent processes. The spray wash process, which is placed at the beginning, is used to loosen the strong contaminants and clean particles from the surface. Depending on the contamination type and structure, spray wash might be needed as a pre-process. After drying and rust prevention, another spray wash process can be used to improve the quality of the surface. Spray wash cleaning can be applied with different pressure and temperature. It gives the remanufacturer a chance to get great surface finishing with post spray wash cleaning.

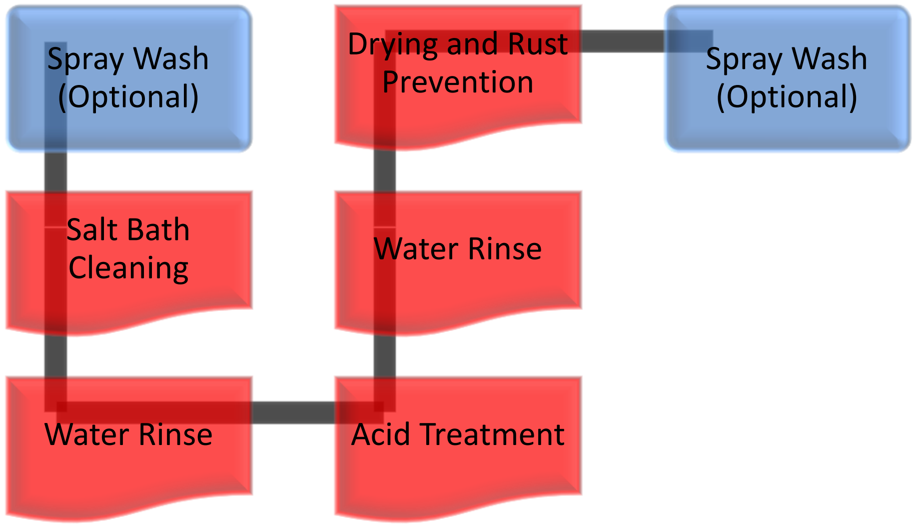


Figure 54 - Molten Salt Cleaning Flow Chart

The demonstration was specifically designed to show most effective and suitable cleaning processes for the piston contamination thickness and type. All possible of contamination levels, including low, medium and high thicknesses, and contamination types, including organic, inorganic, and organic-inorganic mixture, were considered. Based on this information, system design selections are made with the software.

With contamination and part data, we can eliminate some processes and find a cleaning process that is a good fit given all previous considerations. Also, applicable contingent processes are determined for the each major process. These contingent processes are not necessary to use with the major processes but as shown on the results, when these processes are combined with main process cleaning result is greatly improved. Contingent processes might have higher system cost for the piston surface cleaning, but depending on the customer objectives each system can be improved with additional pre or post processes. Based on this demonstration, we can see that for piston cleaning, a high variety of cleaning processes can be designed based on the customer's objective and the type and thickness of contamination. Such a selection process could be mirrored in a wide variety of applications and produce similar results to aid engineers, system designers, and customers in creating a system that best meets the needs of each specific remanufacturing concern.

CHAPTER V

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

Many different cleaning processes can be used for different industries to clean a variety of contaminants with high efficiency and satisfaction. This study shows that cleaning process design and selection play an important role in the remanufacturing field. Companies have increased their investigation into sustainability, but very little research currently exists. Consequently, more research and information is needed in this field. This thesis will fill some gaps in the remanufacturing and cleaning process fields. Additionally, the software created for this project is helpful for different users to find suitable processes for their system.

The surface cleaning methods, post and pre cleaning processes and cleaning process outputs were summarized through literature review in this study. Cleaning methods were studied with specific attention to the details of mechanism, pre and post processes, cost, environmental impact, energy consumption, process time and cleaning result for each cleaning process. In order to synthesize these varying data points into a single decision-making interface, user-friendly software was created to generate the all possible main, pre and post processes depending on the user’s input. When the user inputs the contamination type with which they are working, the software shows all applicable cleaning processes as well as a comparison of other decision-making parameters such as energy consumption, environmental impact, cost, process time, and cleaning result. This study and the software that resulted from it are really important in allowing the user to find all possible cleaning processes with and without contingent process with their cleanness, energy consumption, process time, environmental impact and cost analysis and comparison. Additional research results are discussed below:

- All useful chemical cleaners, their characteristics and used cleaning processes are summarized in this study. This helps the user to select correct chemical type when they need to use chemicals in their cleaning process.
- For all main cleaning processes, including laser cleaning, abrasive blasting cleaning, ultrasonic cleaning, vibratory cleaning, thermal cleaning, molten salt cleaning and immersion cleaning, cleaning characteristics, flow charts and designs were created and shown with schemas.
- Each of the cleaning methods was categorized based on cleaning principle and contamination type. The cleaning principle is the broad description of each cleaning process. For example, laser cleaning, a cleaning principle, may include cleaning processes like steam laser cleaning and dry laser cleaning. The categorization of cleaning methods included an explanation of each cleaning principle type and each process' applicable contamination type, contamination level, cleaning system type, material type, chemicals (if needed), temperature, cycle time, efficiency, operator needs, energy consumption, emission level and system cost based on previous research.
- Major contamination growth and cleaning process efficiency mathematical models were found during the literature review.

- Software was created that generates an output for total energy consumption, processing time, system cost, environmental impact, and cleaning results for any selected processes. Outputs are based on the range of performance found in literature.
- A piston cleaning demonstration was created based on previous research found regarding contamination and material type. Possible main, pre and post cleaning methods were generated from software, and generated results are compared and best applicable process results were shown.

5.2 Future Research Work

5.2.1 Problems of Current Research

The remanufacturing system design and selection steps and evaluation method introduced in this study provides a natural guide to future research. Typically, in this research a new domain will initially be studied at the shallow levels of the remanufacturing system design and optimization, after which research on the subject will gradually move to deeper levels. For example, most of cleaning method cleanliness models are found from the literature studied at the shallowest level (output optimization); in recent years, most research in this field has focused on mathematical modeled mechanism design, the second gap in the output optimization; and most recently, these mathematical models can also be created for other cleaning factors. Therefore, energy consumption, environmental impact, and cycle time can be created with experimental designs. Instead of using a model, previous research process results provided a range, so in future research this result can be more accurate with models. In recent research, studies focus exclusively at the level in remanufacturing cleaning process selection. Created software gives highly satisfied result on main, pre and post cleaning methods selection. In future research mathematical models can improve the software by implementing models instead of ranges. So, these changes give user more accurate results on software. Also software only provides the main, pre and post cleaning methods, but future research also can be focused on software improvement with process flow with pre and post cleaning methods. Hence, directions for future research include pushing existing domains deeper down with this research, as well as introducing new domains or formalizing, optimization and software improvement.

While the cleaning process selection and optimization proposed in this study provides a high level guideline to future research, the research contributions at the individual points of the remanufacturing cleaning process suggest many more specific open questions and directions. This section will lay out some of these more immediately accessible avenues for future research.

5.2.2 Outcome Optimization

In section 3.1.2, each cleaning method was shown with the mathematical models of cleaning results. These models were found from previous research in literature, which applied for same type of cleaning research and methods with experiments to create the model. This research is focused only for process selection and finds the best possible method for the user. Therefore, only previous research ranges are based on process selection result. Selections are made based on their part and condition. It is already discussed how the models can be extended to apply to optimize the result, but we do not yet have experimental results on the efficacy of doing so. It would also be interesting to find research that has the effect of making the preprocessing and experiment techniques sufficient to solve the optimization problem and create new models.

Another research gap in this study regarding optimization is other cleaning outputs' result accuracy. In this research outputs were based on the range of performance found in literature, but these results' accuracy is not completely satisfying to the user. To improve the result and satisfy the user, mathematical models need to be used. In literature, there is currently no research on this particular subject. So on future research, different cleaning processes' energy consumption, process time, and environmental impact models can be created with experimental settings. Main type of contaminant layers and their mathematical models are found from other particular research and represented in section 3.1.3 in this study. These contamination thickness growth models are a significant variable for cleaning processes' energy consumption, process time, and environmental impact models. For creating these mathematical models, an experimental result has to be used to experimentally test the scalability of the mixed integer and linear modeling formulations of the clearing problem.

The outcome optimization gaps and future research subjects are determined above but this research creates a base for future research. Future research can potentially address this in the way of experimental design. Experimental results are the only way to improve cleaning results, energy consumption, environmental impact and process time.

5.2.3 Software Improvement

Result Improvement: This recent research was introduced in section 4.1, Remanufacturing System Selection, and this software allows the user to find the most suitable processes depending on input. Also, the software gives the user a chance to compare environmental impact, energy consumption, cleanliness, process time and cost based on a range found in literature. This is a big step for users to be able to make their own selection and find correct cleaning method. The software generates these results based on the contamination level and contamination type. The cleaning method is a most significant factor for the environmental impact results. As mentioned, just a range is not going to give the user an exact result, but it helps to make a decision with close results and accurate approximations.

So, the future research can be created with using this gap in this recent study. As mentioned above, models have to be implemented with the software to increase the result accuracy. Cleanliness result can be given using exact thickness after each process if a model is created correctly and used with the software. Therefore, the customer will need more inputs than is available with the current software. The same changes can be applied for environmental impact, energy consumption and process time factor results. Such research can be exhaustive, and software results can be improved with these of changes. In its current form, the software's only application is to find suitable main, pre and post cleaning processes and result from the range, but if the models will be included to software, it can be used as process selection and result filter. With accurate results, the user can be more satisfied and find out the cleaning process cost for each part exactly given their specifications. After these changes, the user can use cost estimations to consider the payback period of a new plant. Also, cleaning results can be more accurate as thickness is considered, and the user can have more information about the result of designed system. These changes can help the user to find out how a new system's design result matches with their objectives.

Design Improvement: Software design can satisfy the customer on the results page. As shown in the figures from previous sections, it is pretty convenient to see all the results and compare the output with pre and post cleaning results. The software was designed to be user friendly, allowing customers to put the input and get the results. To increase customer satisfaction, some changes can be applied on software. Future research can potentially address this in several ways.

First, future research should design a work flow for each cleaning result. In the demonstration section of this research, a work flow was designed for that specific process but it can be implemented with the software to give the more visual impact of system design. The user can clearly see the steps which have to be created for each selected system. The current design shows the process, but not each step required. For example, the software result will only show molten salt cleaning, but this cleaning method includes salt bath cleaning, water rinse, acid treatment, second water rinse and drying and rust prevention steps. So each major cleaning process' steps can be shown with details on the software. Also after pre and post cleaning processes are determined, each cleaning process result can be shown under each process. So this can be another type of change for the software.

Next, the design of the software gives the results based on customer input, but it does not show the strengths and advantages of each process. So the user has to check all the parameter results and compare across processes themselves. But if the software showed results such as "more environmentally friendly," "less energy needed," "lowest cycle time," and "highest effectiveness" on cleaning results, that can help the user make the best system selection.

The last and most important area for future research is on model implementation of the software. As mentioned on section 5.2.2, new models can be created based on experimental designs of cleanliness, environmental impact, energy consumption, and process time factors. These models can be applied to the software and it will generate a very accurate result based on the user's input. The software will require more inputs from the user to generate the possible main cleaning, pre cleaning, post cleaning and these cleaning mathematical results. This gives the user solid and exact numbers when using the software. Because the software has already been created, this next step would be critical for improving results for users.

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APPENDIX A

APPENDIX A

SOFTWARE CODES

Project file

```
#-------------------------------------------------
#
# Project created by QtCreator 2012-06-28T12:46:57
#
#-------------------------------------------------
QT += core gui
TARGET = ozan
TEMPLATE = app
SOURCES += main.cpp\
mainwindow.cpp \
response.cpp \
titleframe.cpp
HEADERS += mainwindow.h \
response.h \
titleframe.h
win32:RC_FILE += myapp.rc
RESOURCES += \
resource.qrc \
resource.qrc
#include <QtGui/QApplication>
#include "mainwindow.h"
```

main.cpp

```
int main(int argc, char *argv[])
{
QApplication a(argc, argv);
MainWindow w;
a.setWindowIcon(QIcon(":/images/15-14.ico"));
w.setWindowTitle("SG Manufacturing Process Filter v3.1");
w.show();
return a.exec();
}
```

mainwindow.h

```
#ifndef MAINWINDOW_H
#define MAINWINDOW_H
#include <QtGui>
#include <QtDebug>
#include <map>
#include "response.h"
using namespace std;
class MainWindow : public QWidget
{
```

```
Q_OBJECT
public:
explicit MainWindow();
~MainWindow();
private slots:
void update();
void zeroize();
void updateConType(int option);
private:
void populate();
QHBoxLayout *h1;
QVBoxLayout *v1;
QVBoxLayout *v2;
QLabel *label1;
QComboBox *q1;
QLabel *label2;
QComboBox *q2;
QLabel *label3;
QComboBox *q3;
QLabel *label4;
QComboBox *q4;
QVBoxLayout *mLayout;
QPushButton *enter;
QHBoxLayout *h2;
Response *res[8];
Response *createRes(int id, int thick);
int translate13();
void initData();
multimap<int,int>process;
multimap<int,int>::iterator it;
pair <multimap<int,int>::iterator,multimap<int,int>::iterator> ret;
int numResBox;
QLabel *result;
};
#endif // MAINWINDOW_H
```

mainwindow.cpp

```
#include "mainwindow.h"
#include "QTextEdit"
MainWindow::MainWindow()
{
h1 = new QHBoxLayout;
v1 = new QVBoxLayout;
v2 = new QVBoxLayout;
label4 = new QLabel("Thickness");
q4 = new QComboBox;
v1->addWidget(label4);
v2->addWidget(q4);
label1 = new QLabel("Contamination type");
q1 = new QComboBox;
v1->addWidget(label1);
v2->addWidget(q1);
label2 = new QLabel("Material Type");
q2 = new QComboBox;
v1->addWidget(label2);
v2->addWidget(q2);
label3 = new QLabel("Geometry");
```

```
q3 = new QComboBox;
v1->addWidget(label3);
v2->addWidget(q3);
h1->addLayout(v1);
h1->addLayout(v2);
h1->addStretch(1);
enter = new QPushButton;
enter->setText("Submit");
h2 = new QHBoxLayout;
h2->addWidget(enter);
h2->addStretch();
result = new QLabel();
mLayout = new QVBoxLayout;
mLayout->addLayout(h1);
mLayout->addLayout(h2);
populate();
mLayout->setSizeConstraint(QLayout::SetFixedSize);
setLayout(mLayout);
numResBox = 0;
connect(enter, SIGNAL(clicked()), this, SLOT(update()));
connect(q1,SIGNAL(currentIndexChanged(int)),this, SLOT(zeroize()));
connect(q2,SIGNAL(currentIndexChanged(int)),this, SLOT(zeroize()));
connect(q3,SIGNAL(currentIndexChanged(int)),this, SLOT(zeroize()));
connect(q4,SIGNAL(currentIndexChanged(int)),this, SLOT(updateConType(int)));
initData();
}
void MainWindow::updateConType(int option) {
q1->clear();
switch(option) {
case 0:
q1->addItem("Organic");
q1->addItem("Inorganic");
break;
case 1:
q1->addItem("Organic");
q1->addItem("Inorganic");
q1->addItem("Organic & Mix");
break;
case 2:
q1->addItem("Organic");
q1->addItem("Inorganic");
q1->addItem("Organic & Mix");
q1->addItem("Organic & Mix & Inorganic");
break;
}
}
void MainWindow::zeroize() {
qDebug() << "change!";
mLayout->removeWidget(result);
result->hide();
qDebug() << numResBox;
if (numResBox > 0) {
for (int i = 0; i < numResBox; i++) {
mLayout->removeWidget(res[i]);
res[i]->hide();
}
```

```
// not using delete[] res; because res is not dynamic array :)
mLayout->update();
qDebug()<< "deleted";
}
}
Response* MainWindow::createRes(int id, int thick) {
return new Response(id, thick);
}
MainWindow::~MainWindow()
{
}
void MainWindow::populate() {
q1->addItem("Organic");
q1->addItem("Inorganic");
q2->addItem("Soft Metal");
q2->addItem("Hard Metal");
q2->addItem("Other");
q3->addItem("Complex");
q3->addItem("Simple");
q4->addItem("Low");
q4->addItem("Medium");
q4->addItem("High");
}
void MainWindow::update() {
// it = process.find(translate13());
// qDebug() << (*it).first << "->" << (*it).second ;
zeroize();
numResBox = 0;
ret = process.equal_range(translate13());
mLayout->addWidget(result);
for (it = ret.first; it != ret.second; it++) {
res[numResBox] = createRes((*it).second,q4->currentIndex());
mLayout->addWidget(res[numResBox]);
numResBox++;
qDebug() << (*it).first << "->" << (*it).second;
}
QString msg = QString("%1 cleaning process(es) available for given
constraints.").arg(numResBox);
result->setText(msg);
result->show();
qDebug() << "total box" << numResBox;
}
int MainWindow::translate13() {
return q1->currentIndex()*100 + q2->currentIndex()*10 + q3->currentIndex();
}
void MainWindow::initData() {
process.insert(pair<int,int>(11,1));
process.insert(pair<int,int>(21,1));
process.insert(pair<int,int>(111,1));
process.insert(pair<int,int>(121,1));
process.insert(pair<int,int>(211,1));
process.insert(pair<int,int>(221,1));
process.insert(pair<int,int>(311,1));
process.insert(pair<int,int>(321,1));
process.insert(pair<int,int>(1,2));
process.insert(pair<int,int>(11,2));
```

```
process.insert(pair<int,int>(21,2));
process.insert(pair<int,int>(101,2));
process.insert(pair<int,int>(111,2));
process.insert(pair<int,int>(121,2));
process.insert(pair<int,int>(201,2));
process.insert(pair<int,int>(211,2));
process.insert(pair<int,int>(221,2));
process.insert(pair<int,int>(301,2));
process.insert(pair<int,int>(311,2));
process.insert(pair<int,int>(321,2));
process.insert(pair<int,int>(0,3));
process.insert(pair<int,int>(10,3));
process.insert(pair<int,int>(20,3));
process.insert(pair<int,int>(100,3));
process.insert(pair<int,int>(110,3));
process.insert(pair<int,int>(120,3));
process.insert(pair<int,int>(200,3));
process.insert(pair<int,int>(210,3));
process.insert(pair<int,int>(220,3));
process.insert(pair<int,int>(1,3));
process.insert(pair<int,int>(11,3));
process.insert(pair<int,int>(21,3));
process.insert(pair<int,int>(101,3));
process.insert(pair<int,int>(111,3));
process.insert(pair<int,int>(121,3));
process.insert(pair<int,int>(201,3));
process.insert(pair<int,int>(211,3));
process.insert(pair<int,int>(221,3));
process.insert(pair<int,int>(310,3));
process.insert(pair<int,int>(311,3));
process.insert(pair<int,int>(10,4));
process.insert(pair<int,int>(11,4));
process.insert(pair<int,int>(110,4));
process.insert(pair<int,int>(111,4));
process.insert(pair<int,int>(210,4));
process.insert(pair<int,int>(211,4));
process.insert(pair<int,int>(310,4));
process.insert(pair<int,int>(311,4));
process.insert(pair<int,int>(0,5));
process.insert(pair<int,int>(10,5));
process.insert(pair<int,int>(20,5));
process.insert(pair<int,int>(1,5));
process.insert(pair<int,int>(11,5));
process.insert(pair<int,int>(21,5));
process.insert(pair<int,int>(10,6));
process.insert(pair<int,int>(11,6));
process.insert(pair<int,int>(0,7));
process.insert(pair<int,int>(1,7));
process.insert(pair<int,int>(10,7));
process.insert(pair<int,int>(11,7));
process.insert(pair<int,int>(20,7));
process.insert(pair<int,int>(21,7));
process.insert(pair<int,int>(100,7));
process.insert(pair<int,int>(101,7));
process.insert(pair<int,int>(110,7));
process.insert(pair<int,int>(111,7));
```

```
process.insert(pair<int,int>(120,7));
process.insert(pair<int,int>(121,7));
process.insert(pair<int,int>(11,8));
process.insert(pair<int,int>(111,8));
process.insert(pair<int,int>(211,8));
process.insert(pair<int,int>(311,8));
}
```

response.h

```
#ifndef RESPONSE_H
#define RESPONSE_H
#include <QtGui>
#include <QtDebug>
#include <QFrame>
#include <map>
#include "titleframe.h"
using namespace std;
class ConProcess : public QFrame
{
Q_OBJECT
public:
ConProcess();
ConProcess(int thick, int before, int process, int after, int after2, int result);
private:
QVBoxLayout *box;
QLabel *title;
QLabel *time;
QLabel *energy;
QLabel *envi;
QLabel *clean;
QLabel *contigent;
QString getCap(int conNum, bool isAfter2);
double getTime(int before, int process, int after, int after2, int thick);
double getEnergy(int before, int process, int after, int after2, int thick);
int getSysCost(int before, int process, int after, int after2, bool isLow );
double rangeSelect(double min, double max, int opt) {
if (opt == 0) return min;
return (opt == 2)?max: (max+min)/2;
}
};
class Response : public QFrame
{
Q_OBJECT
public:
Response();
Response(int id, int thick);
signals:
void clicked();
public slots:
void changeDim();
private:
QHBoxLayout *container;
QVBoxLayout *box;
QVBoxLayout *titleBox;
QLabel *label1;
QLabel *label2;
QLabel *label3;
```

```
QLabel *label4;
QLabel *label5;
QLabel *label6;
QLabel *title;
QLabel *time;
QLabel *energy;
QLabel *envi;
QLabel *clean;
QLabel *contigent;
ConProcess *cProcess[4];
TitleFrame *tFrame;
int clickNum;
multimap<int,int>conPro;
multimap<int,int>::iterator it;
pair <multimap<int,int>::iterator,multimap<int,int>::iterator> ret;
int numConBox;
int _thick;
int _process;
double rangeSelect(double min, double max, int opt) {
if (opt == 0) return min;
return (opt == 2)?max: (max+min)/2;
}
int encodeKey(int process, int thickness);
int encodeValue(int before, int present, int after, int after2, int result);
int decodeKey(int codedValue, char option);
int decodeValue(int codedValue, char option);
void update();
void zeroize();
void initData();
void minimize(int option);
void mousePressEvent(QMouseEvent *event);
};
#endif // RESPONSE_H
```

response.cpp

```
#include "response.h"
ConProcess::ConProcess(int thick, int before, int process, int after, int after2, int result) {
box = new QVBoxLayout;
QString envImp[8];
envImp[0] = QString("Low");
envImp[1] = QString("High");
envImp[2] = QString("Low");
envImp[3] = QString("High");
envImp[4] = QString("Average");
envImp[5] = QString("High");
envImp[6] = QString("Low");
envImp[7] = QString("Average");
QString r[5];
r[0] = QString("Low");
r[1] = QString("Average");
r[2] = QString("Good");
r[3] = QString("High");
r[4] = QString("Very High");
QString caption = QString("%1 \n%2 %3");
QString c = QString("%1 ");
QString t = QString("%1 min");
QString e = QString("%1 kw per cycle");
```

```
QString env = QString("%1 ");
QString cost = QString("$%1K - $%2K");
//!!! validator needed!! subject to error!
//helper function needed here such that would return before Spray wash or before after...
//all done!
caption = caption.arg(getCap(before,false), getCap(after, false), getCap(after2, true));
env = env.arg(envImp[process]);
t = t.arg(getTime(before, process,after,after2,thick));
e = e.arg(getEnergy(before, process,after,after2,thick));
c = c.arg((result > 0 && result < 6)?r[result-1]:"Invalid value!" );
cost = cost.arg(getSysCost(before, process,after,after2,true)).arg(getSysCost(before,
process,after,after2,false));
title = new QLabel(caption);
time = new QLabel(t);
energy = new QLabel(e);
envi = new QLabel(env);
clean = new QLabel(c);
contigent = new QLabel(cost);
title->setStyleSheet("QLabel { color : blue; }");
time->setStyleSheet("QLabel { color : blue; }");
energy->setStyleSheet("QLabel { color : blue; }");
envi->setStyleSheet("QLabel { color : blue; }");
clean->setStyleSheet("QLabel { color : blue; }");
contigent->setStyleSheet("QLabel { color : blue; }");
box->addWidget(title);
box->addWidget(time);
box->addWidget(energy);
box->addWidget(envi);
box->addWidget(clean);
box->addWidget(contigent);
box->setSizeConstraint(QLayout::SetFixedSize);
setLayout(box);
}
double ConProcess::getTime(int before, int process, int after, int after2,int thick) {
double bL, bU;
double pL, pU;
double aL, aU;
double a2L, a2U;
double timeL[8];
timeL[0] = 1;
timeL[1] = 2;
timeL[2] = 10;
timeL[3] = 10;
timeL[4] = 2.5;
timeL[5] = 15;
timeL[6] = 1;
timeL[7] = 5;
double timeU[8];
timeU[0] = 2;
timeU[1] = 30;
timeU[2] = 30;
timeU[3] = 30;
timeU[4] = 6;
timeU[5] = 60;
timeU[6] = 4;
timeU[7] = 30;
```

```
if (before > 0 && before < 9) {
bL = timeL[before - 1];
bU = timeU[before - 1];
} else {
bL = 0;
bU = 0;
}
if (after > 0 && after < 9) {
aL = timeL[after - 1];
aU = timeU[after - 1];
} else {
aL = 0;
aU = 0;
}
if (after2 > 0 && after2 < 9) {
a2L = timeL[after2 - 1];
a2U = timeU[after2 - 1];
} else {
a2L = 0;
a2U = 0;
}
if (process > 0 && process < 9) {
pL = timeL[process - 1];
pU = timeU[process - 1];
} else {
pL = 0;
pU = 0;
}
return rangeSelect(bL+pL+aL+a2L, bU+pU+aU+a2U, thick );
}
double ConProcess::getEnergy(int before, int process, int after,int after2, int thick) {
double bL, bU;
double pL, pU;
double aL, aU;
double a2L, a2U;
double energyL[8];
energyL[0]= 2;
energyL[1]= 1.2;
energyL[2]= 0.8;
energyL[3]= 3;
energyL[4]= 1;
energyL[5]= 3;
energyL[6]= 0.2;
energyL[7]= 0.1;
double energyU[8];
energyU[0]= 12;
energyU[1]= 4.7;
energyU[2]= 0.9;
energyU[3]= 4.5;
energyU[4]= 2.4;
energyU[5]= 6;
energyU[6]= 0.8;
energyU[7]= 1.2;
if (before > 0 && before < 9) {
bL = energyL[before - 1];
bU = energyU[before - 1];
```

```
} else {
bL = 0;
bU = 0;
}
if (after > 0 && after < 9) {
aL = energyL[after - 1];
aU = energyU[after - 1];
} else {
aL = 0;
aU = 0;
}
if (after2 > 0 && after2 < 9) {
a2L = energyL[after2 - 1];
a2U = energyU[after2 - 1];
} else {
a2L = 0;
a2U = 0;
}
if (process > 0 && process < 9) {
pL = energyL[process - 1];
pU = energyU[process - 1];
} else {
pL = 0;
pU = 0;
}
return rangeSelect(bL+pL+aL+a2L, bU+pU+aU+a2U, thick );
}
int ConProcess::getSysCost(int before, int process, int after, int after2, bool isLow) {
int bL, bU;
int pL, pU;
int aL, aU;
int a2L, a2U;
int sysCostL[8];
sysCostL[0] = 65;
sysCostL[1] = 15;
sysCostL[2] = 10;
sysCostL[3] = 9;
sysCostL[4] = 5;
sysCostL[5] = 8;
sysCostL[6] = 2;
sysCostL[7] = 3;
int sysCostU[8];
sysCostU[0] = 430;
sysCostU[1] = 95;
sysCostU[2] = 180;
sysCostU[3] = 60;
sysCostU[4] = 85;
sysCostU[5] = 54;
sysCostU[6] = 8;
sysCostU[7] = 20;
if (before > 0 && before < 9) {
bL = sysCostL[before - 1];
bU = sysCostU[before - 1];
} else {
bL = 0;
bU = 0;
```

```
}
if (after > 0 && after < 9) {
aL = sysCostL[after - 1];
aU = sysCostU[after - 1];
} else {
aL = 0;
aU = 0;
}
if (after2 > 0 && after2 < 9) {
a2L = sysCostL[after2 - 1];
a2U = sysCostU[after2 - 1];
} else {
a2L = 0;
a2U = 0;
}
if (process > 0 && process < 9) {
pL = sysCostL[process - 1];
pU = sysCostU[process - 1];
} else {
pL = 0;
pU = 0;
}
return (isLow)? (bL + pL + aL + a2L) : (bU + pU + aU + a2U);
}
QString ConProcess::getCap(int conNum, bool isAfter2) {
QString capList[8];
capList[0]="Laser Cleaning";
capList[1]="Abrasive Blasting Cleaning";
capList[2]="Ultrasonic Cleaning";
capList[3]="Molten Salt Cleaning";
capList[4]="Immersion Cleaning";
capList[5]="Thermal Cleaning";
capList[6]="Spray Wash";
capList[7]="Vibratory Cleaning";
qDebug() << "isAfter2" << isAfter2;
if (conNum > 0 && conNum < 9) {
qDebug() << "isAfter2" << isAfter2;
return (isAfter2)? QString("\n").append(capList[conNum - 1]):capList[conNum - 1];
}
else {
return (isAfter2)? QString("\n"):QString("None");
}
}
ConProcess::ConProcess() {
ConProcess(0,0,0,0,0,0);
}
Response::Response(){
Response(0,0);
}
Response::Response(int id, int thick)
{
_thick = thick;
_process = id;
initData();
box = new QVBoxLayout;
titleBox = new QVBoxLayout;
```

```
container = new QHBoxLayout;
QString caption = QString("%1");
QString c = QString("%1");
QString t = QString("%1 min");
QString e = QString("%1 kw per cycle");
QString env = QString("%1");
QString cost = QString("%1");
switch (id) {
case 1:
caption = caption.arg("Laser Cleaning");
t = t.arg(rangeSelect(1,2, thick));
e = e.arg(rangeSelect(2,12, thick));
env = env.arg("Low");
c = c.arg("High");
cost = cost.arg("$65000 - $430000");
break;
case 2:
caption = caption.arg("Abrasive Blasting Cleaning");
t = t.arg(rangeSelect(2,30, thick));
e = e.arg(rangeSelect(1.2,4.7, thick));
env = env.arg("High");
c = c.arg("Average");
cost = cost.arg("$15000 - $95000");
break;
case 3:
caption = caption.arg("Ultrasonic Cleaning");
t = t.arg(rangeSelect(10,30, thick));
e = e.arg(rangeSelect(0.8,0.9, thick));
env = env.arg("Low");
c = c.arg("Average");
cost = cost.arg("$10000 - $180000");
break;
case 4:
caption = caption.arg("Molten Salt Cleaning");
t = t.arg(rangeSelect(10,30, thick));
e = e.arg(rangeSelect(3,4.5, thick));
env = env.arg("High");
c = c.arg("Average");
cost = cost.arg("$9000 - $60000");
break;
case 5:
caption = caption.arg("Immersion Cleaning");
t = t.arg(rangeSelect(2.5,6, thick));
e = e.arg(rangeSelect(1,2.4, thick));
env = env.arg("Average");
c = c.arg("Low");
cost = cost.arg("$5000 - $85000");
break;
case 6:
caption = caption.arg("Thermal Cleaning");
t = t.arg(rangeSelect(15,60, thick));
e = e.arg(rangeSelect(3,6, thick));
env = env.arg("High");
c = c.arg("Low");
cost = cost.arg("$8000 - $54000");
break;
```

```
case 7:
caption = caption.arg("Spray Wash");
t = t.arg(rangeSelect(1,4, thick));
e = e.arg(rangeSelect(0.2,0.8, thick));
env = env.arg("Low");
c = c.arg("Low");
cost = cost.arg("$2000 - $8000");
break;
case 8:
caption = caption.arg("Vibratory Cleaning");
t = t.arg(rangeSelect(5,30, thick));
e = e.arg(rangeSelect(0.1,1.2, thick));
env = env.arg("Average");
c = c.arg("Low");
cost = cost.arg("$3000 - $20000");
break;
default:
break;
}
title = new QLabel(caption);
time = new QLabel(t);
energy = new QLabel(e);
envi = new QLabel(env);
clean = new QLabel(c);
contigent = new QLabel(cost);
label1 = new QLabel("Cleaning Type:");
label2 = new QLabel("Time:");
label3 = new QLabel("Energy Consumption:");
label4 = new QLabel("Environmental Impact:");
label5 = new QLabel("Cleaning Result:");
label6 = new QLabel("System Cost:");
titleBox->addWidget(label1);
titleBox->addWidget(label2);
titleBox->addWidget(label3);
titleBox->addWidget(label4);
titleBox->addWidget(label5);
titleBox->addWidget(label6);
titleBox->setSizeConstraint(QLayout::SetFixedSize);
container->addLayout(titleBox);
box->addWidget(title);
box->addWidget(time);
box->addWidget(energy);
box->addWidget(envi);
box->addWidget(clean);
box->addWidget(contigent);
box->setSizeConstraint(QLayout::SetFixedSize);
container->addLayout(box);
tFrame = new TitleFrame();
container->addWidget(tFrame);
update();
setLayout(container);
this->setFrameStyle(1);
connect(this,SIGNAL(clicked()),this,SLOT(changeDim()));
minimize(1);
clickNum = 1;
}
```

```
void Response::mousePressEvent(QMouseEvent *event){
clickNum++ ;
emit clicked();
}
void Response::changeDim() {
qDebug() << clickNum % 2;
minimize(clickNum % 2);
}
void Response::minimize(int option) {
if (option == 0) {
label2->show();
label3->show();
label4->show();
label5->show();
label6->show();
time->show();
energy->show();
envi->show();
clean->show();
contigent->show();
for (int i = 0; i < numConBox; i++) {
cProcess[i]->show();
}
tFrame->setMin(true);
}
else {
label2->hide();
label3->hide();
label4->hide();
label5->hide();
label6->hide();
time->hide();
energy->hide();
envi->hide();
clean->hide();
contigent->hide();
for (int i = 0; i < numConBox; i++) {
cProcess[i]->hide();
}
tFrame->setMin(false);
}
box->update();
}
void Response::initData() {
conPro.insert(pair<int,int>(10, 1705));
conPro.insert(pair<int,int>(11, 1705));
conPro.insert(pair<int,int>(12, 71005));
conPro.insert(pair<int,int>(12, 71705));
conPro.insert(pair<int,int>(20, 2705));
conPro.insert(pair<int,int>(21, 2703));
conPro.insert(pair<int,int>(21, 32004));
conPro.insert(pair<int,int>(21, 72004));
conPro.insert(pair<int,int>(21, 32705));
conPro.insert(pair<int,int>(22, 2703));
conPro.insert(pair<int,int>(22, 32004));
conPro.insert(pair<int,int>(22, 32705));
```

```
conPro.insert(pair<int,int>(22, 72005));
conPro.insert(pair<int,int>(30, 3705));
conPro.insert(pair<int,int>(31, 3703));
conPro.insert(pair<int,int>(31, 3875)); //##############
conPro.insert(pair<int,int>(31, 73704));
conPro.insert(pair<int,int>(32, 3703));
conPro.insert(pair<int,int>(32, 3875)); //##############
conPro.insert(pair<int,int>(32, 73704));
conPro.insert(pair<int,int>(40, 4705));
conPro.insert(pair<int,int>(41, 4705));
conPro.insert(pair<int,int>(42, 4704));
conPro.insert(pair<int,int>(42, 74705));
conPro.insert(pair<int,int>(50, 5703));
conPro.insert(pair<int,int>(51, 5702));
conPro.insert(pair<int,int>(51, 75703));
conPro.insert(pair<int,int>(52, 5702));
conPro.insert(pair<int,int>(52, 75703));
conPro.insert(pair<int,int>(60, 6702));
conPro.insert(pair<int,int>(60, 76703));
conPro.insert(pair<int,int>(61, 6702));
conPro.insert(pair<int,int>(61, 76702));
conPro.insert(pair<int,int>(62, 6701));
conPro.insert(pair<int,int>(62, 76702));
conPro.insert(pair<int,int>(80, 8702));
conPro.insert(pair<int,int>(80, 78703));
conPro.insert(pair<int,int>(81, 8702));
conPro.insert(pair<int,int>(81, 78703));
conPro.insert(pair<int,int>(82, 8701));
conPro.insert(pair<int,int>(82, 78702));
}
int Response::encodeKey(int process, int thickness) {
return process *10 + thickness;
}
int Response::encodeValue(int before, int present, int after,int after2, int result) {
return before *10000 + present *1000 + after*100 +after2*10+ result;
}
int Response::decodeKey(int codedValue, char option) {
switch(option) {
case 'p':
return codedValue/10;
break;
case 't':
return codedValue % 10;
break;
}
return -1;
}
int Response::decodeValue(int codedValue, char option) {
int temp = 0;
switch(option) {
case 'b':
return codedValue/10000;
break;
case 'p':
return (codedValue %10000)/1000 ;
break;
```

```
case 'a':
return (codedValue %1000)/100 ;
break;
case '2':
return (codedValue %100)/10 ;
break;
case 'r':
return codedValue %10;
break;
}
return -1;
}
void Response::update() {
//zeroize();
numConBox = 0;
int key = encodeKey(_process,_thick);
int t, b, a, a2, r;
qDebug() << "created key " << key;
ret = conPro.equal_range(key);
for (it = ret.first; it != ret.second; it++) {
t = _thick;
b = decodeValue((*it).second,'b');
a = decodeValue((*it).second,'a');
a2 = decodeValue((*it).second,'2');
r = decodeValue((*it).second,'r');
qDebug() << "after2"<<a2;
cProcess[numConBox] = new ConProcess(t,b,_process,a, a2, r);
container->addWidget(cProcess[numConBox]);
qDebug() << "value = " << (*it).second ;
numConBox++;
}
qDebug() << "total contingent = " << numConBox;
tFrame->setInfo(numConBox);
minimize(1);
container->addStretch(1);
}
void Response::zeroize() {
if (numConBox > 0) {
for (int i = 0; i < numConBox; i++) {
cProcess[i]->hide();
container->removeWidget(cProcess[i]);
}
// not using delete[] cProcess; because res is not dynamic array :)
container->update();
qDebug()<< "deleted";
}
}
```

titleframe.h

```
#ifndef TITLEFRAME_H
#define TITLEFRAME_H
#include <QFrame>
#include <QLabel>
#include <QLayout>
class TitleFrame : public QFrame
{
Q_OBJECT
```

```
public:
TitleFrame();
void setInfo(int number);
void setMin(bool visible);
signals:
public slots:
private:
QVBoxLayout *box;
QLabel *title;
QLabel *time;
QLabel *energy;
QLabel *envi;
QLabel *clean;
QLabel *contigent;
QLabel *info;
QString _info;
int num;
};
#endif // TITLEFRAME_H
```

titleframe.cpp

```
#include "titleframe.h"
TitleFrame::TitleFrame()
{
box = new QVBoxLayout;
title = new QLabel("Cleaning Type Before:\nCleaning Type After:\n");
time = new QLabel("Time:");
energy = new QLabel("Energy Consumption:");
envi = new QLabel("Environmental Impact:");
clean = new QLabel("Cleaning Result:");
contigent = new QLabel("System Cost:");
_info = QString("%1 Contingent Process(es) \n available...");
info = new QLabel(_info);
info->setStyleSheet("QLabel { color : blue; }");
title->setStyleSheet("QLabel { color : blue; }");
time->setStyleSheet("QLabel { color : blue; }");
energy->setStyleSheet("QLabel { color : blue; }");
envi->setStyleSheet("QLabel { color : blue; }");
clean->setStyleSheet("QLabel { color : blue; }");
contigent->setStyleSheet("QLabel { color : blue; }");
box->addWidget(title);
box->addWidget(time);
box->addWidget(energy);
box->addWidget(envi);
box->addWidget(clean);
box->addWidget(contigent);
box->addWidget(info);
setLayout(box);
title->hide();
time->hide();
energy->hide();
envi->hide();
clean->hide();
contigent->hide();
info->show();
this->setFrameStyle(1);
}
```

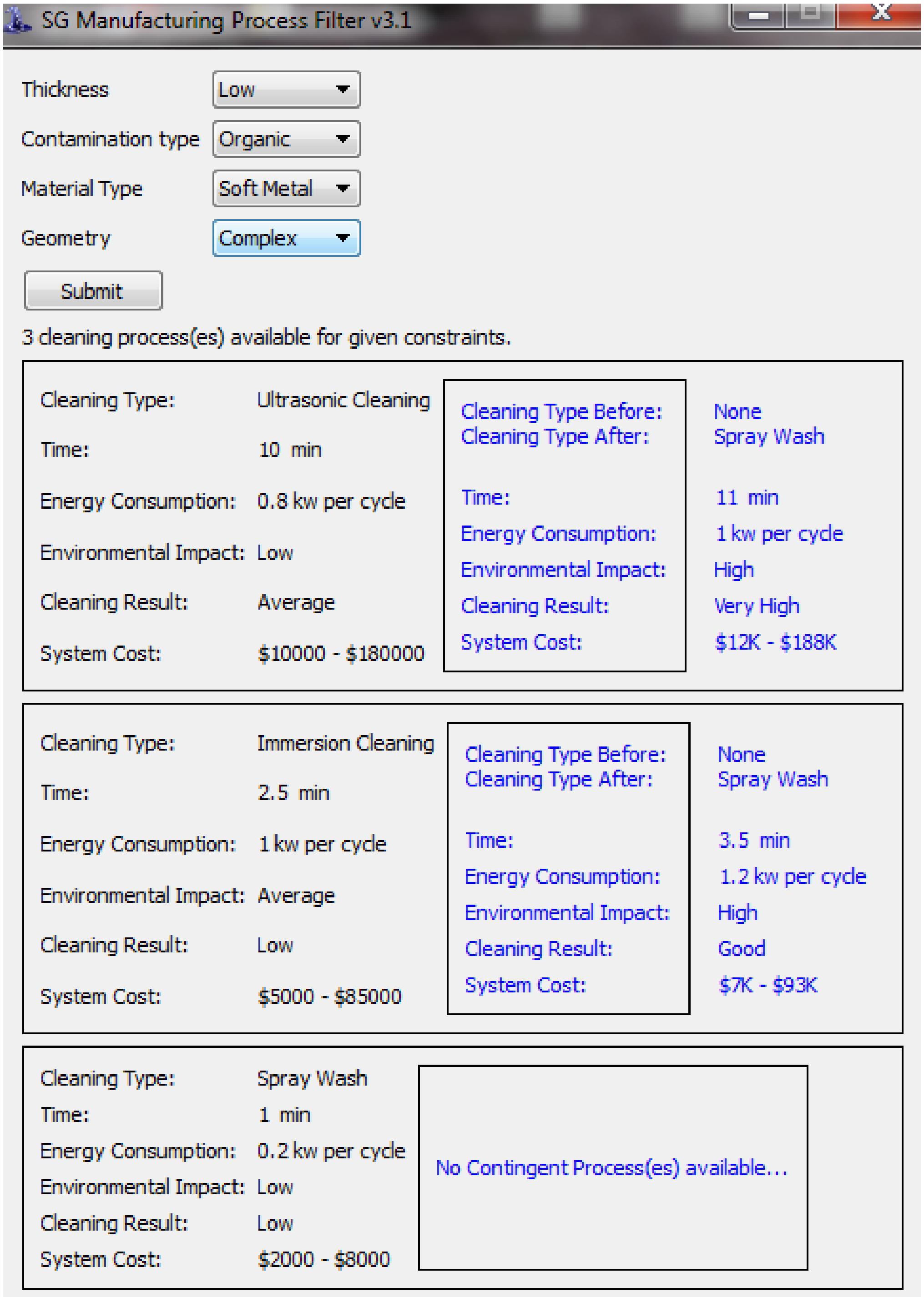
```
void TitleFrame::setMin(bool visible) {
if (num == 0) {
visible = false;
}
if (visible) {
title->show();
time->show();
energy->show();
envi->show();
clean->show();
contigent->show();
info->hide();
}
else {
title->hide();
time->hide();
energy->hide();
envi->hide();
clean->hide();
contigent->hide();
info->show();
}
}
void TitleFrame::setInfo(int number) {
num = number;
if (number > 0) {
_info = QString("%1 Contingent Process(es) available...").arg(number);
}
else {
_info = QString("%1 Contingent Process(es) available...").arg("No");
}
info->setText(_info);
}
```

APPENDIX B

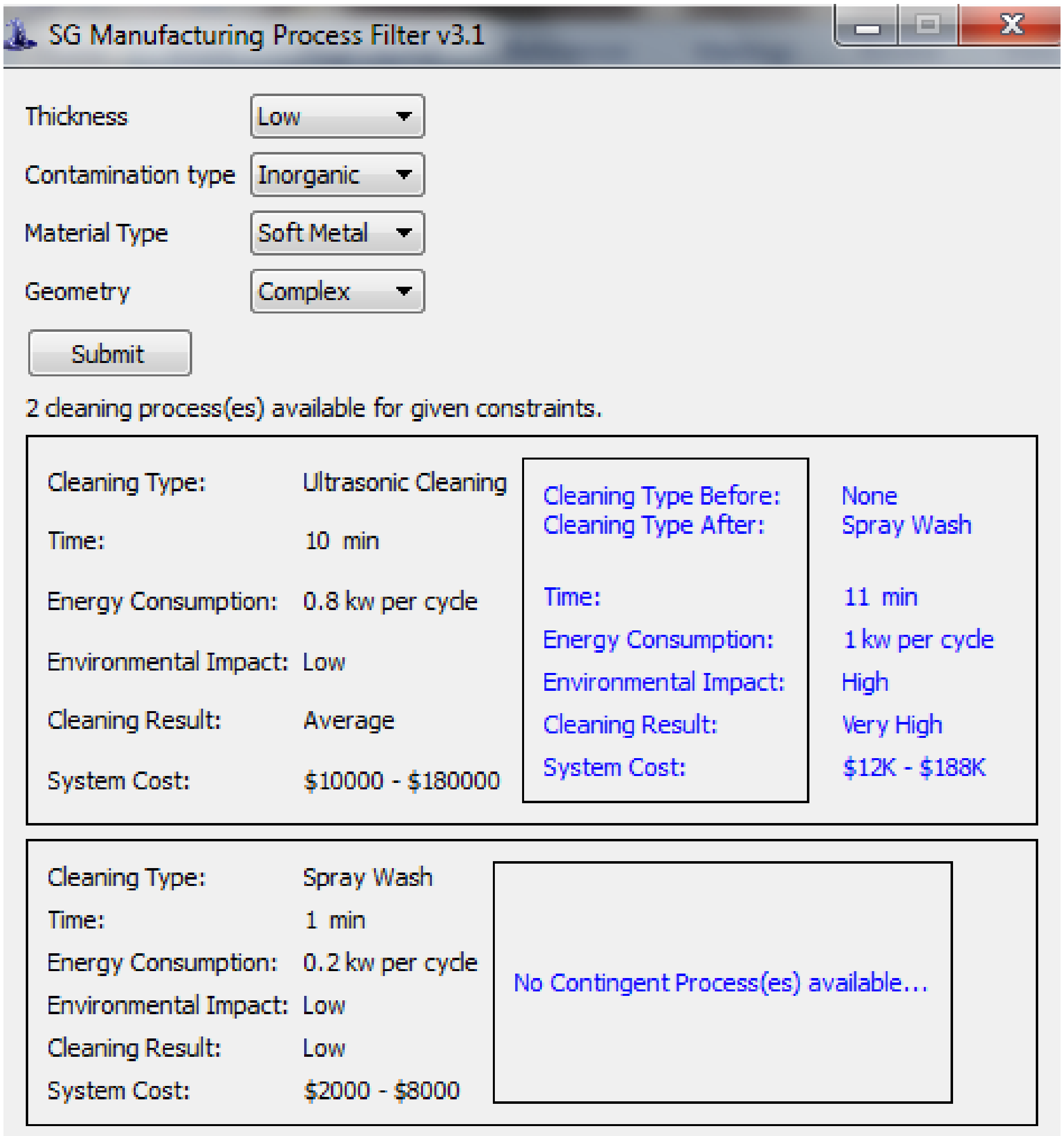
APPENDIX B

SOFTWARE RESULTS

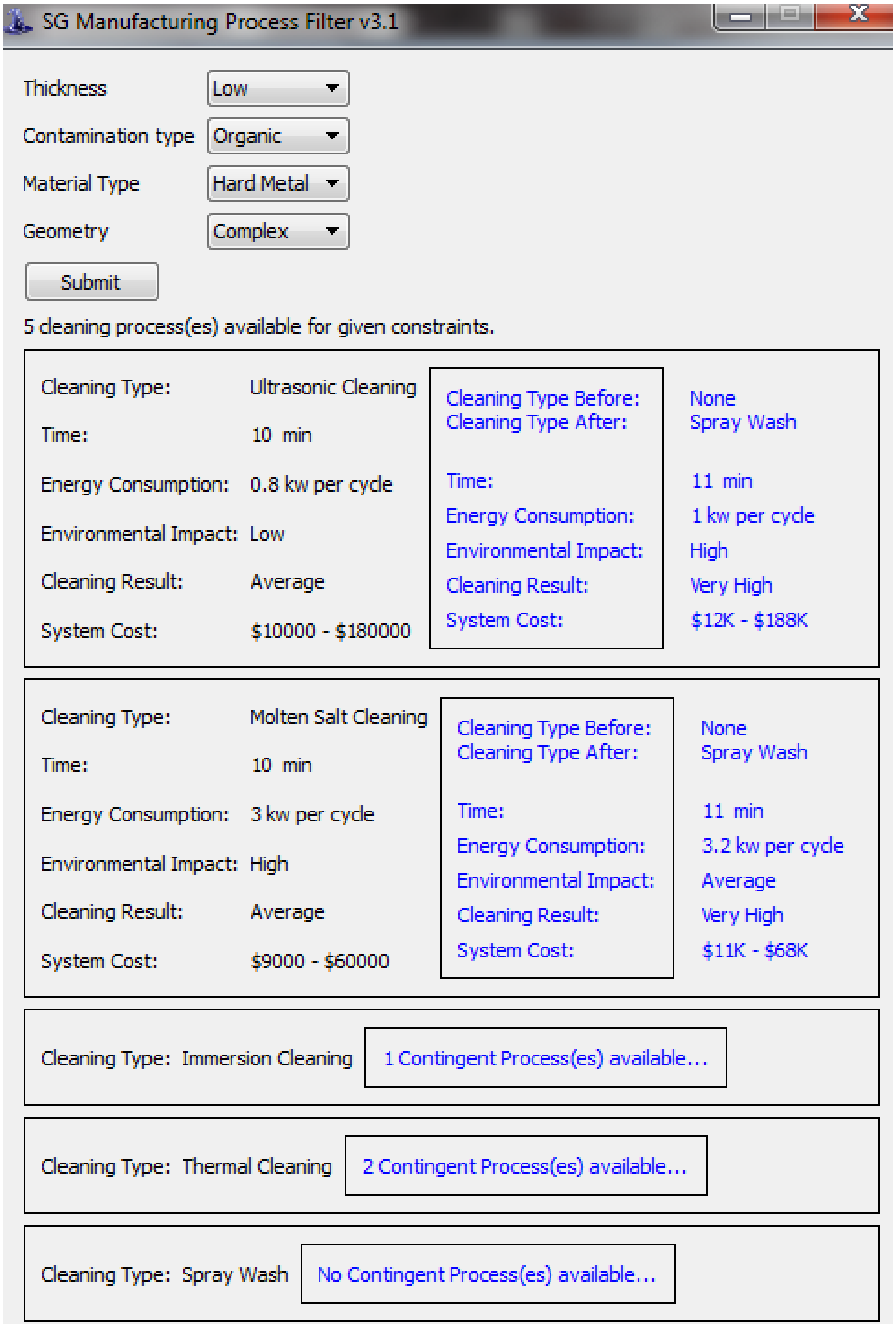
Result 1: Low Organic Contamination Thickness, Soft Metal and Complex Part



Result 2: Low Inorganic Contamination Thickness, Soft Metal and Complex Part

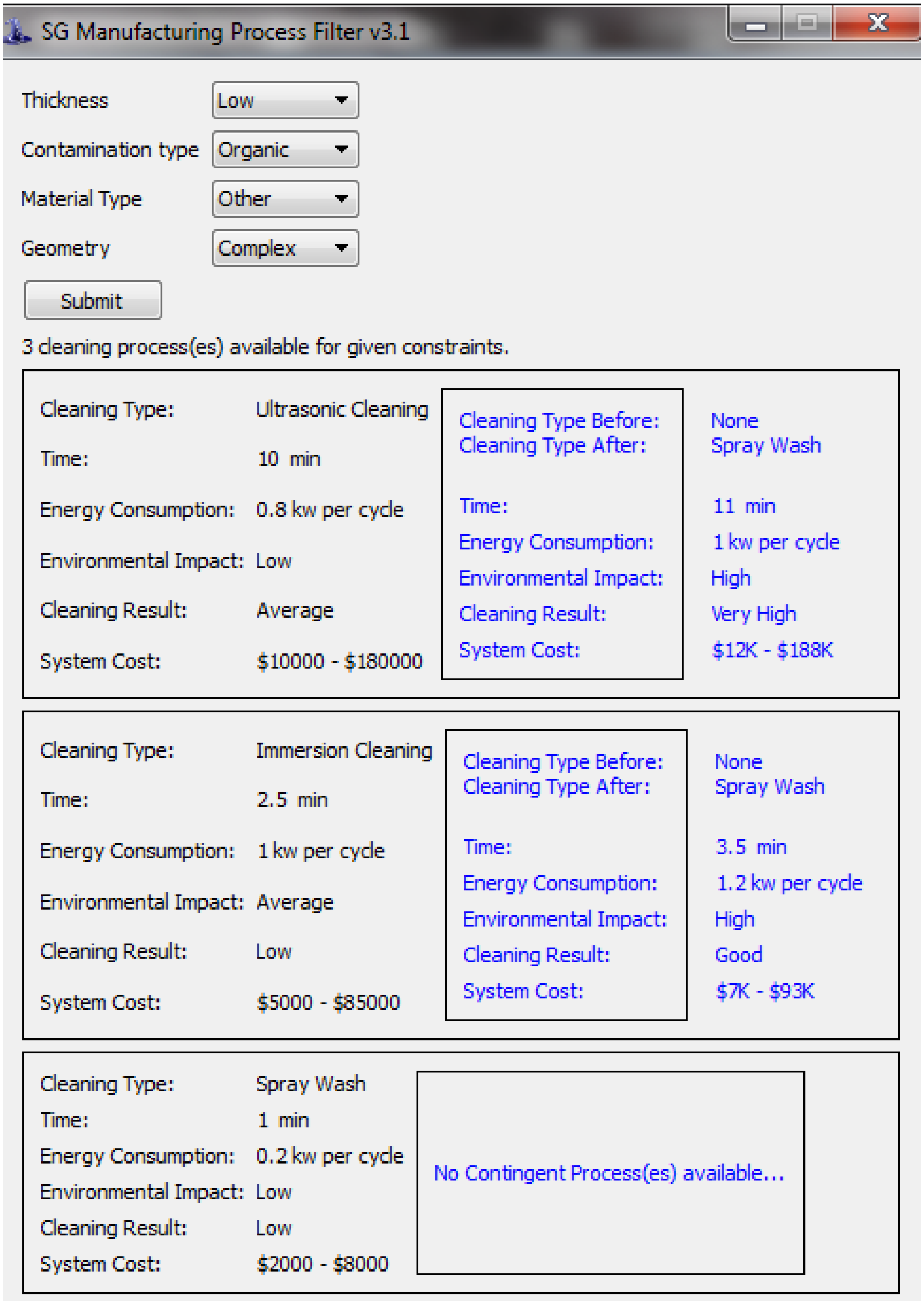


Result 3: Low Organic Contamination Thickness, Hard Metal and Complex Part



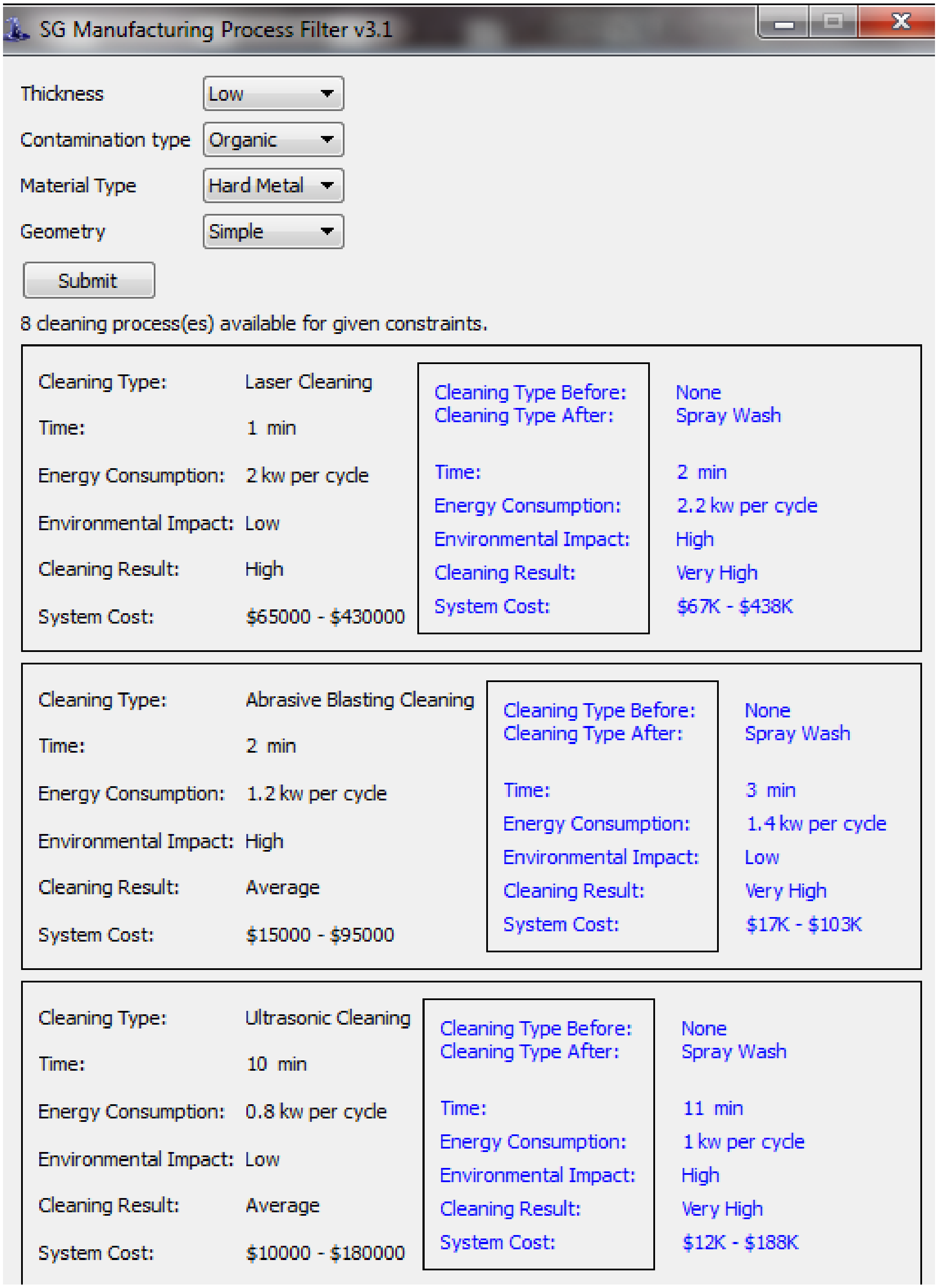

Cleaning Type: Immersion Cleaning
Time: 2.5 min
Energy Consumption: 1 kw per cycle
Environmental Impact: Average
Cleaning Result: Low
System Cost: $5000 - $85000
Cleaning Type Before: None
Cleaning Type After: Spray Wash
Time: 3.5 min
Energy Consumption: 1.2 kw per cycle
Environmental Impact: High
Cleaning Result: Good
System Cost: $7K - $93K
Cleaning Type: Thermal Cleaning
Time: 15 min
Energy Consumption: 3 kw per cycle
Environmental Impact: High
Cleaning Result: Low
System Cost: $8000 - $54000
Cleaning Type Before: None Spray Wash
Cleaning Type After: Spray Wash Spray Wash
Time: 16 min 17 min
Energy Consumption: 3.2 kw per cycle 3.4 kw per cycle
Environmental Impact: Low Low
Cleaning Result: Average Good
System Cost: $10K - $62K $12K - $70K
Cleaning Type: Spray Wash
Time: 1 min
Energy Consumption: 0.2 kw per cycle
Environmental Impact: Low
Cleaning Result: Low
System Cost: $2000 - $8000
No Contingent Process(es) available...

Result 4: Low Organic Contamination Thickness, Other and Complex Part



Result 5: Low Organic Contamination Thickness, Soft Metal and Simple Part

Result 6: Low Organic Contamination Thickness, Hard Metal and Simple Part



Cleaning Type:	Molten Salt Cleaning
Time:	10 min
Energy Consumption:	3 kw per cycle
Environmental Impact:	High
Cleaning Result:	Average
System Cost:	$9000 - $60000

Cleaning Type Before:	None
Cleaning Type After:	Spray Wash
Time:	11 min
Energy Consumption:	3.2 kw per cycle
Environmental Impact:	Average
Cleaning Result:	Very High
System Cost:	$11K - $68K

Cleaning Type:	Immersion Cleaning
Time:	2.5 min
Energy Consumption:	1 kw per cycle
Environmental Impact:	Average
Cleaning Result:	Low
System Cost:	$5000 - $85000

Cleaning Type Before:	None
Cleaning Type After:	Spray Wash
Time:	3.5 min
Energy Consumption:	1.2 kw per cycle
Environmental Impact:	High
Cleaning Result:	Good
System Cost:	$7K - $93K

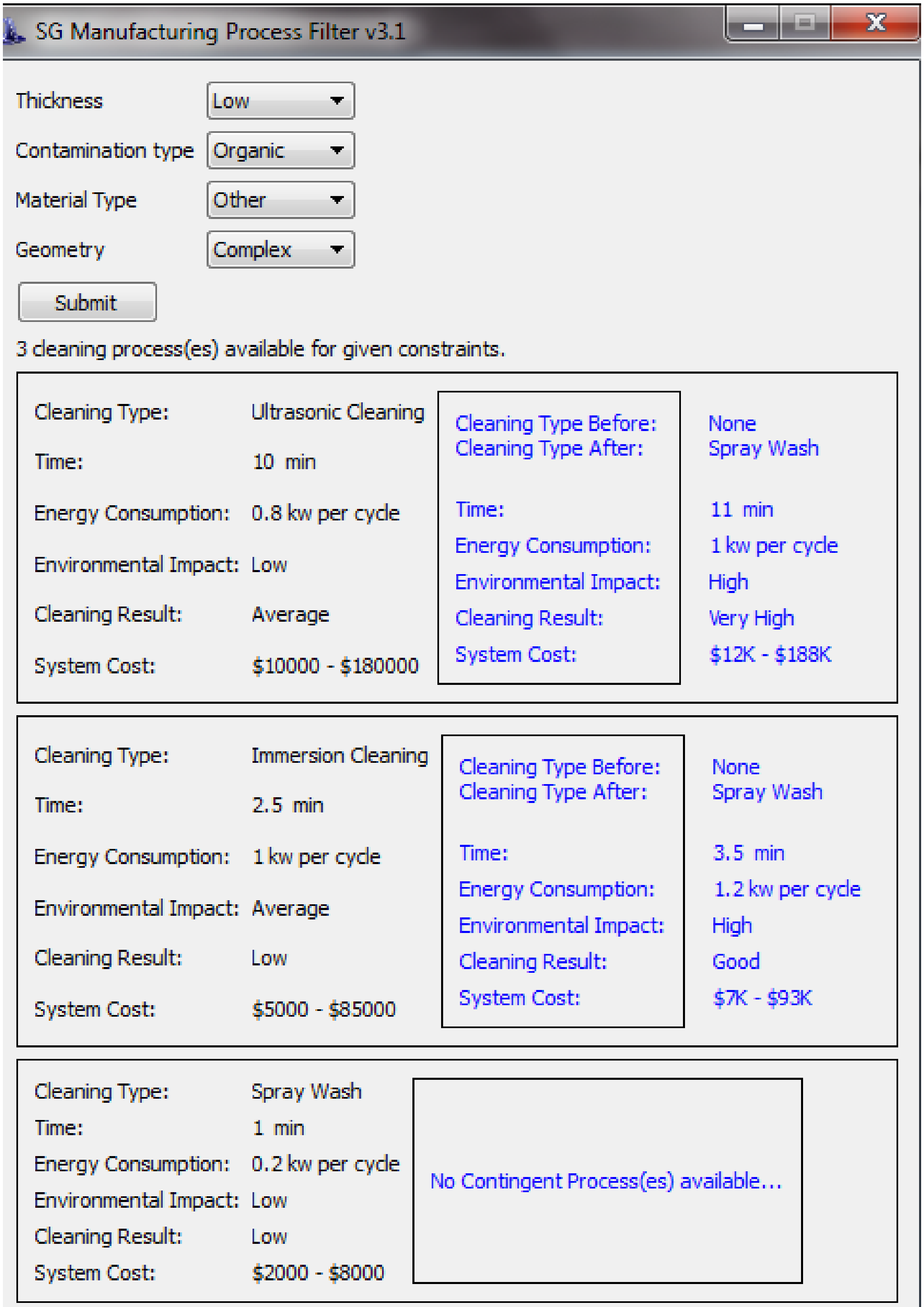
Cleaning Type:	Thermal Cleaning
Time:	15 min
Energy Consumption:	3 kw per cycle
Environmental Impact:	High
Cleaning Result:	Low
System Cost:	$8000 - $54000

Cleaning Type Before:	None	Spray Wash
Cleaning Type After:	Spray Wash	Spray Wash
Time:	16 min	17 min
Energy Consumption:	3.2 kw per cycle	3.4 kw per cycle
Environmental Impact:	Low	Low
Cleaning Result:	Average	Good
System Cost:	$10K - $62K	$12K - $70K

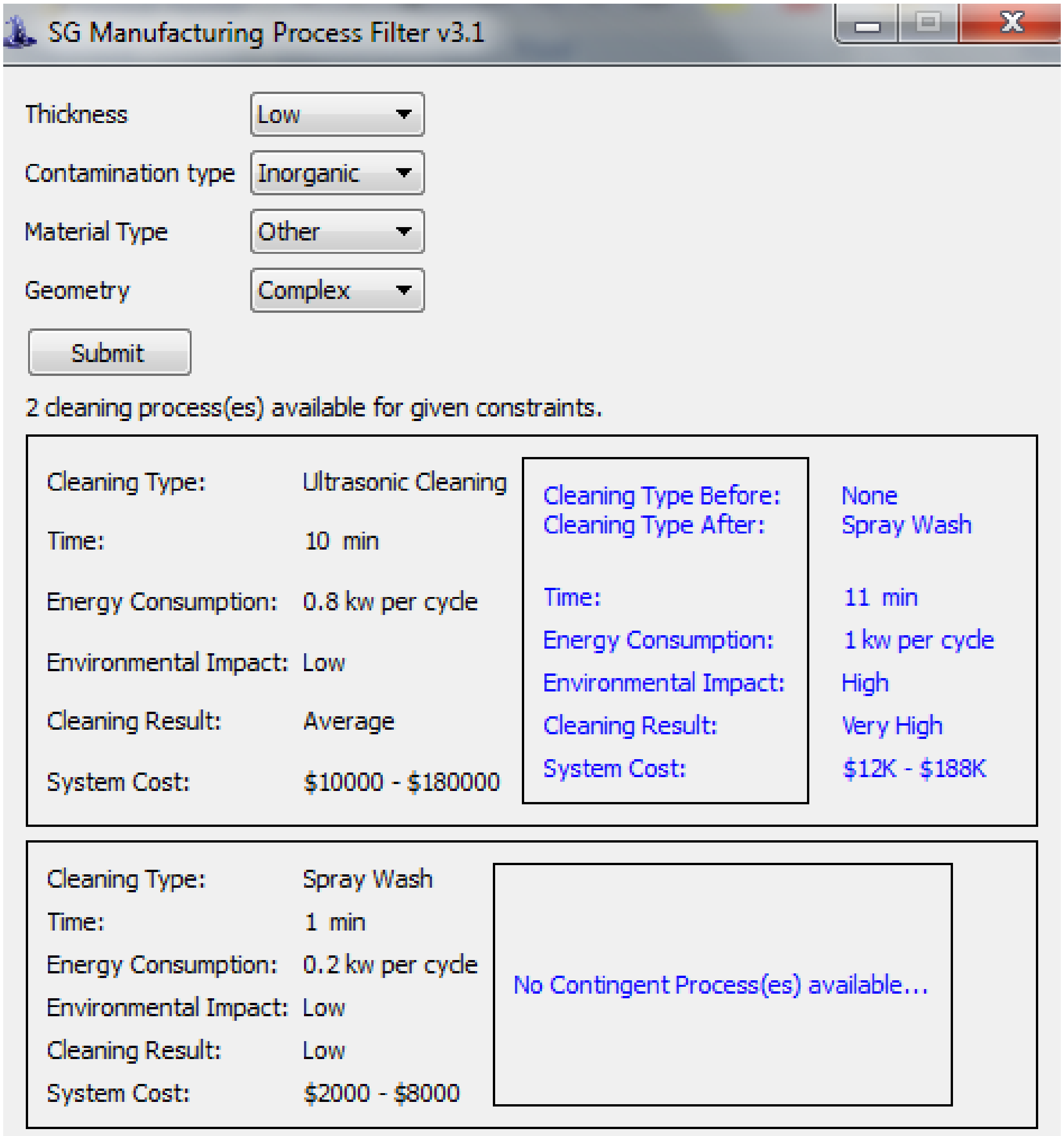
Cleaning Type:	Thermal Cleaning
Time:	15 min
Energy Consumption:	3 kw per cycle
Environmental Impact:	High
Cleaning Result:	Low
System Cost:	$8000 - $54000

Cleaning Type Before:	None	Spray Wash
Cleaning Type After:	Spray Wash	Spray Wash
Time:	16 min	17 min
Energy Consumption:	3.2 kw per cycle	3.4 kw per cycle
Environmental Impact:	Low	Low
Cleaning Result:	Average	Good
System Cost:	$10K - $62K	$12K - $70K

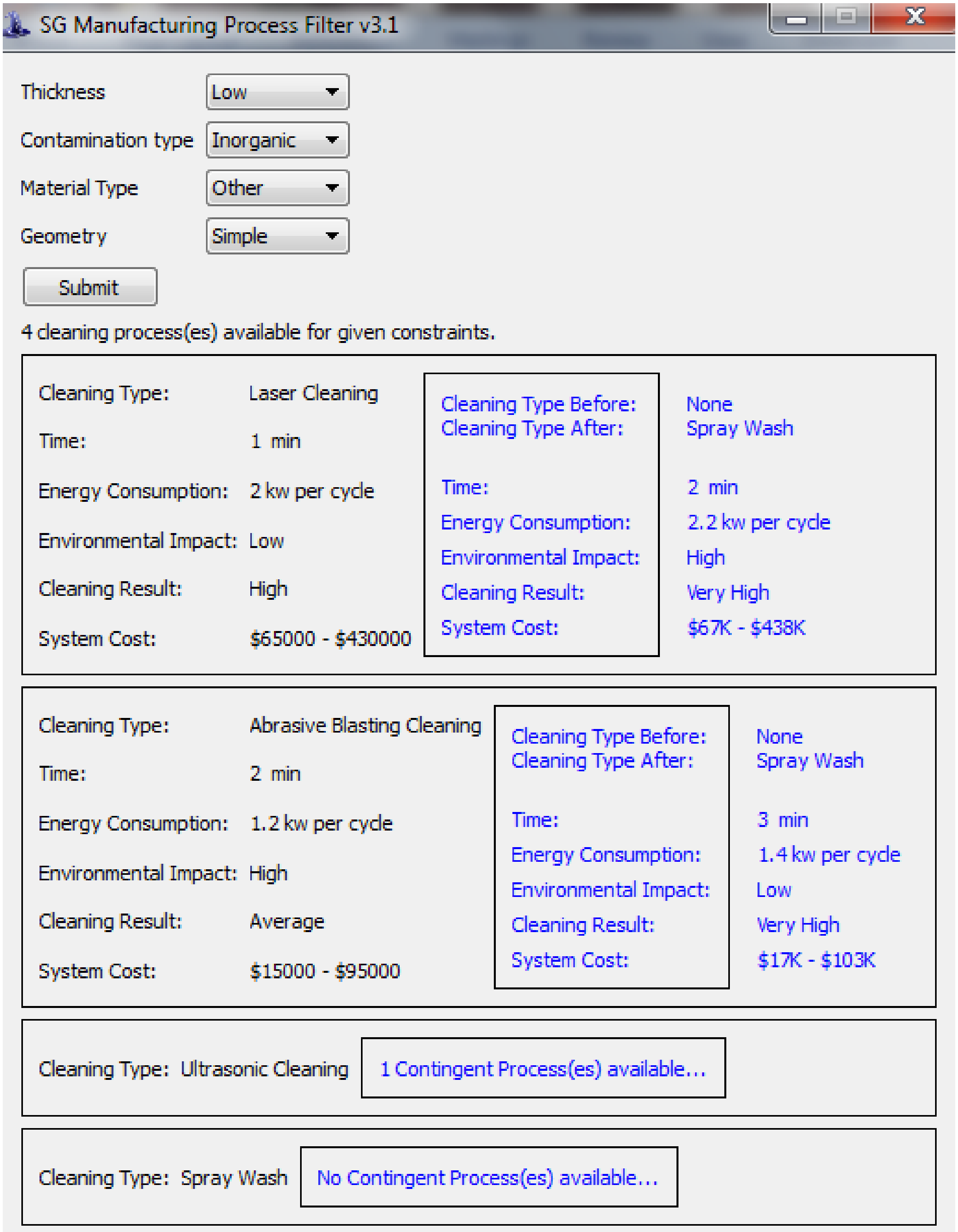
Result 7: Low Organic Contamination Thickness, Other and Complex Part

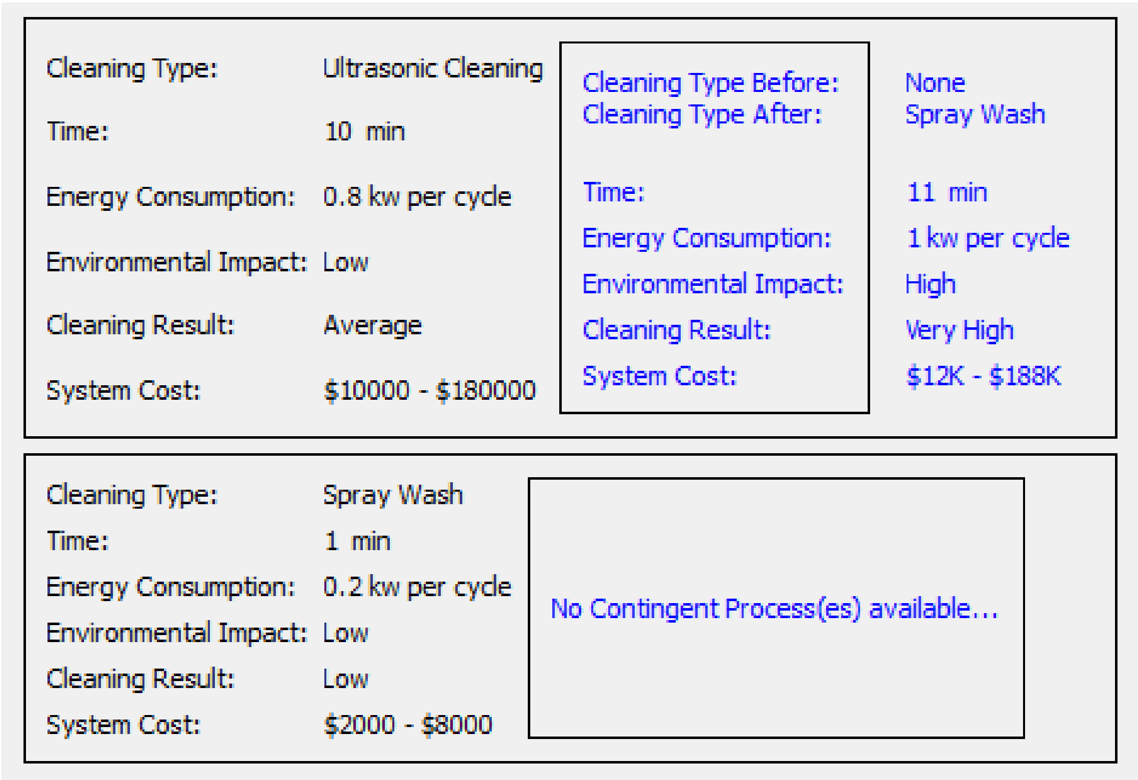


Result 8: Low Inorganic Contamination Thickness, Other and Complex Part

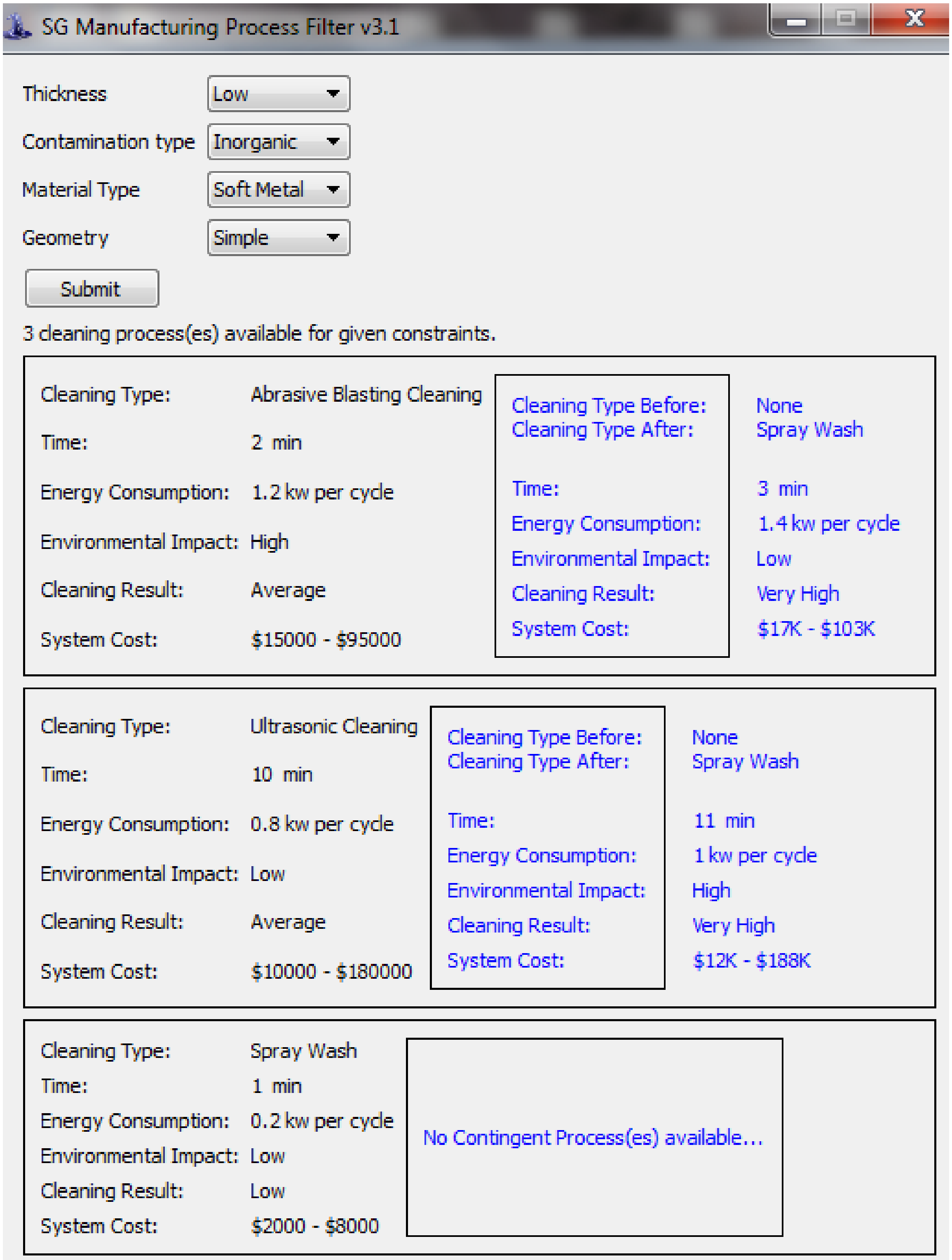


Result 9: Low Inorganic Contamination Thickness, Other and Simple Part




Cleaning Type: Ultrasonic Cleaning
Time: 10 min
Energy Consumption: 0.8 kw per cycle
Environmental Impact: Low
Cleaning Result: Average
System Cost: $10000 - $180000
Cleaning Type Before: None
Cleaning Type After: Spray Wash
Time: 11 min
Energy Consumption: 1 kw per cycle
Environmental Impact: High
Cleaning Result: Very High
System Cost: $12K - $188K
Cleaning Type: Spray Wash
Time: 1 min
Energy Consumption: 0.2 kw per cycle
Environmental Impact: Low
Cleaning Result: Low
System Cost: $2000 - $8000
No Contingent Process(es) available...

Result 10: Low Inorganic Contamination Thickness, Soft and Simple Part



Result 11: Low Inorganic Contamination Thickness, Hard Metal and Simple Part

Cleaning Type:	Molten Salt Cleaning
Time:	10 min
Energy Consumption:	3 kw per cycle
Environmental Impact:	High
Cleaning Result:	Average
System Cost:	$9000 - $60000

Cleaning Type Before:	None
Cleaning Type After:	Spray Wash
Time:	11 min
Energy Consumption:	3.2 kw per cycle
Environmental Impact:	Average
Cleaning Result:	Very High
System Cost:	$11K - $68K

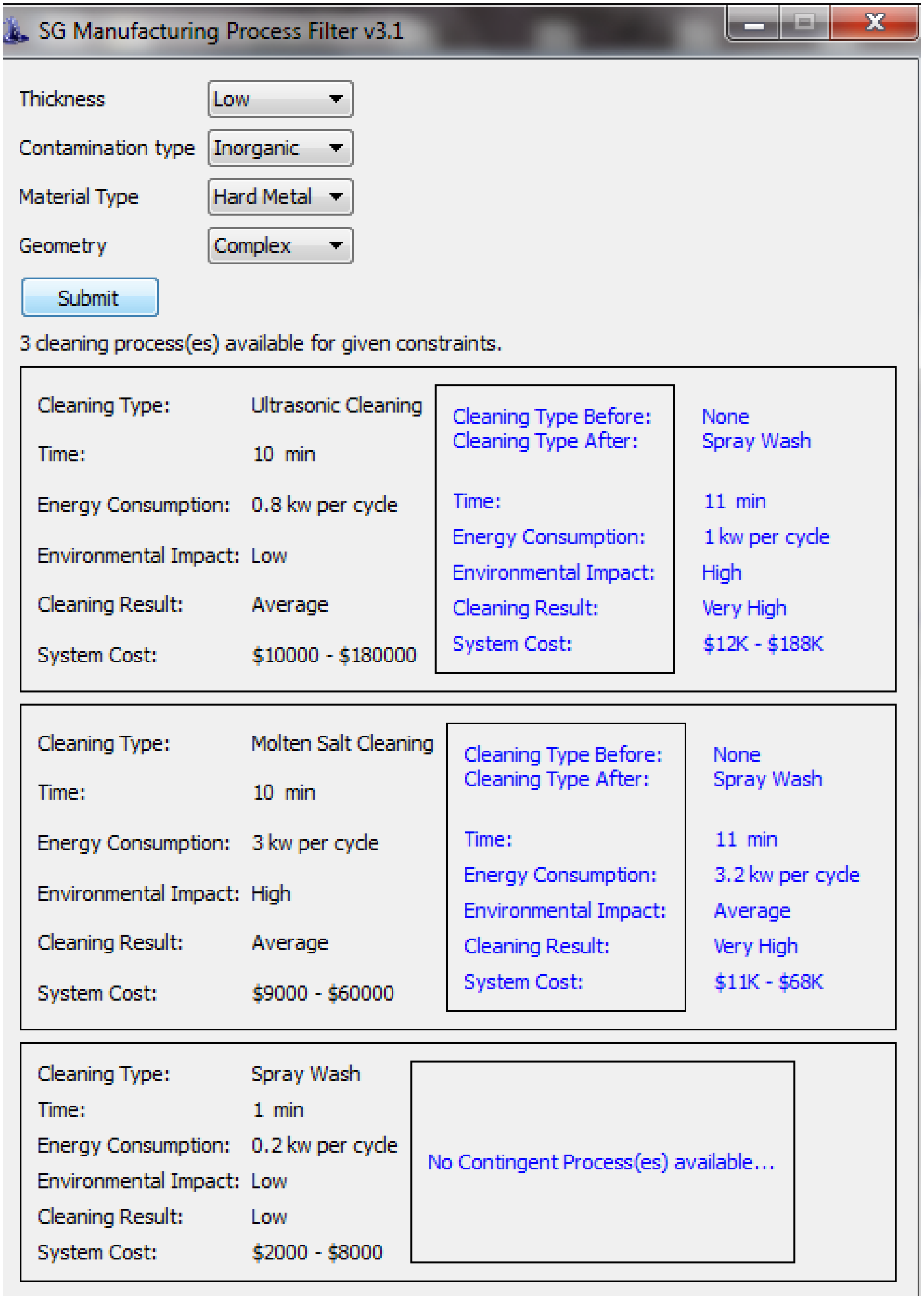
Cleaning Type:	Spray Wash
Time:	1 min
Energy Consumption:	0.2 kw per cycle
Environmental Impact:	Low
Cleaning Result:	Low
System Cost:	$2000 - $8000

No Contingent Process(es) available...

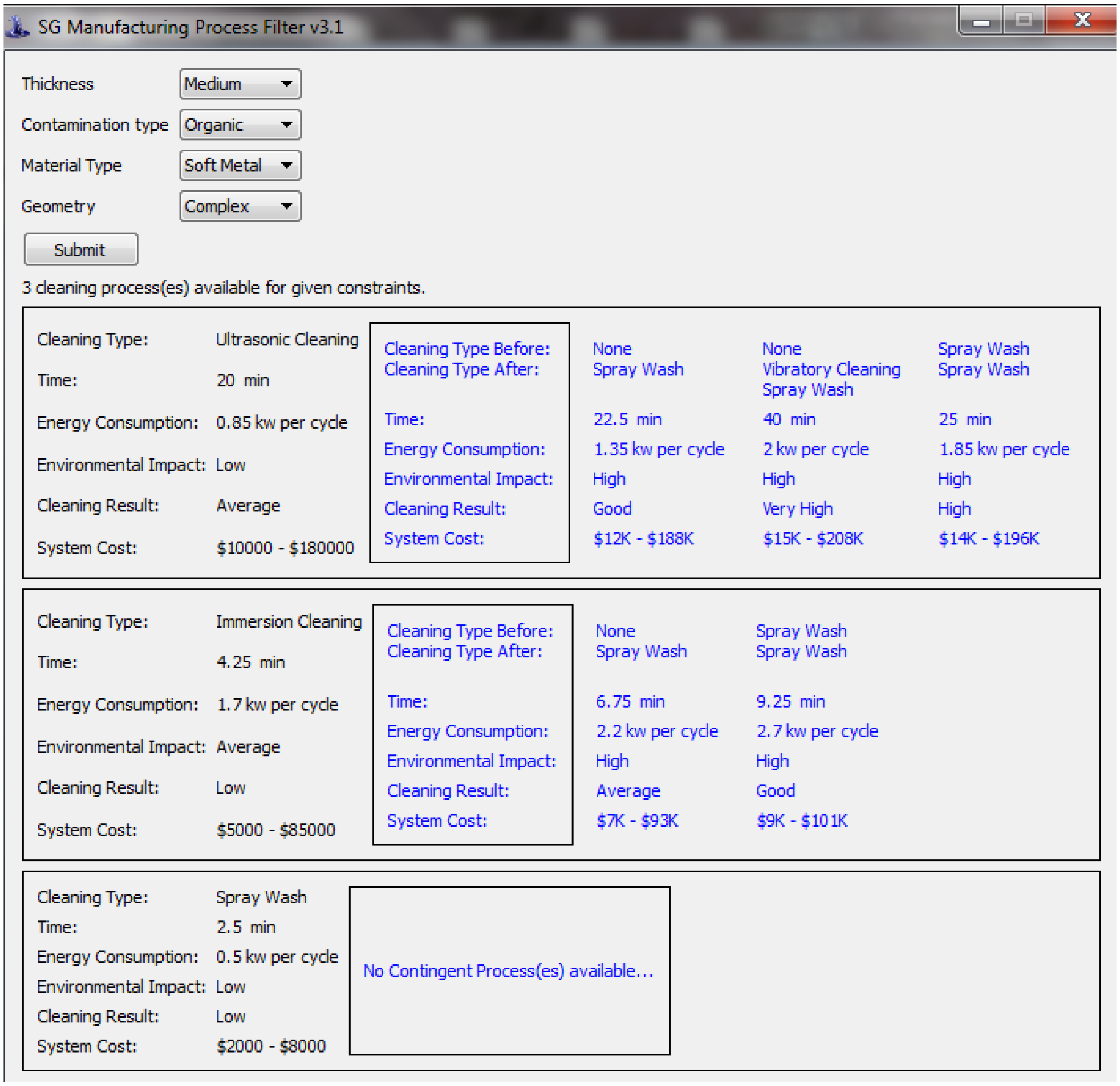
Cleaning Type:	Vibratory Cleaning
Time:	5 min
Energy Consumption:	0.1 kw per cycle
Environmental Impact:	Average
Cleaning Result:	Low
System Cost:	$3000 - $20000

Cleaning Type Before:	None	Spray Wash
Cleaning Type After:	Spray Wash	Spray Wash
Time:	6 min	7 min
Energy Consumption:	0.3 kw per cycle	0.5 kw per cycle
Environmental Impact:	Low	Low
Cleaning Result:	Average	Good
System Cost:	$5K - $28K	$7K - $36K

Result 12: Low Inorganic Contamination Thickness, Hard Metal and Complex Part



Result 13: Medium Organic Contamination Thickness, Soft Metal and Complex Part



Result 14: Medium Organic Contamination Thickness, Hard Metal and Complex Part

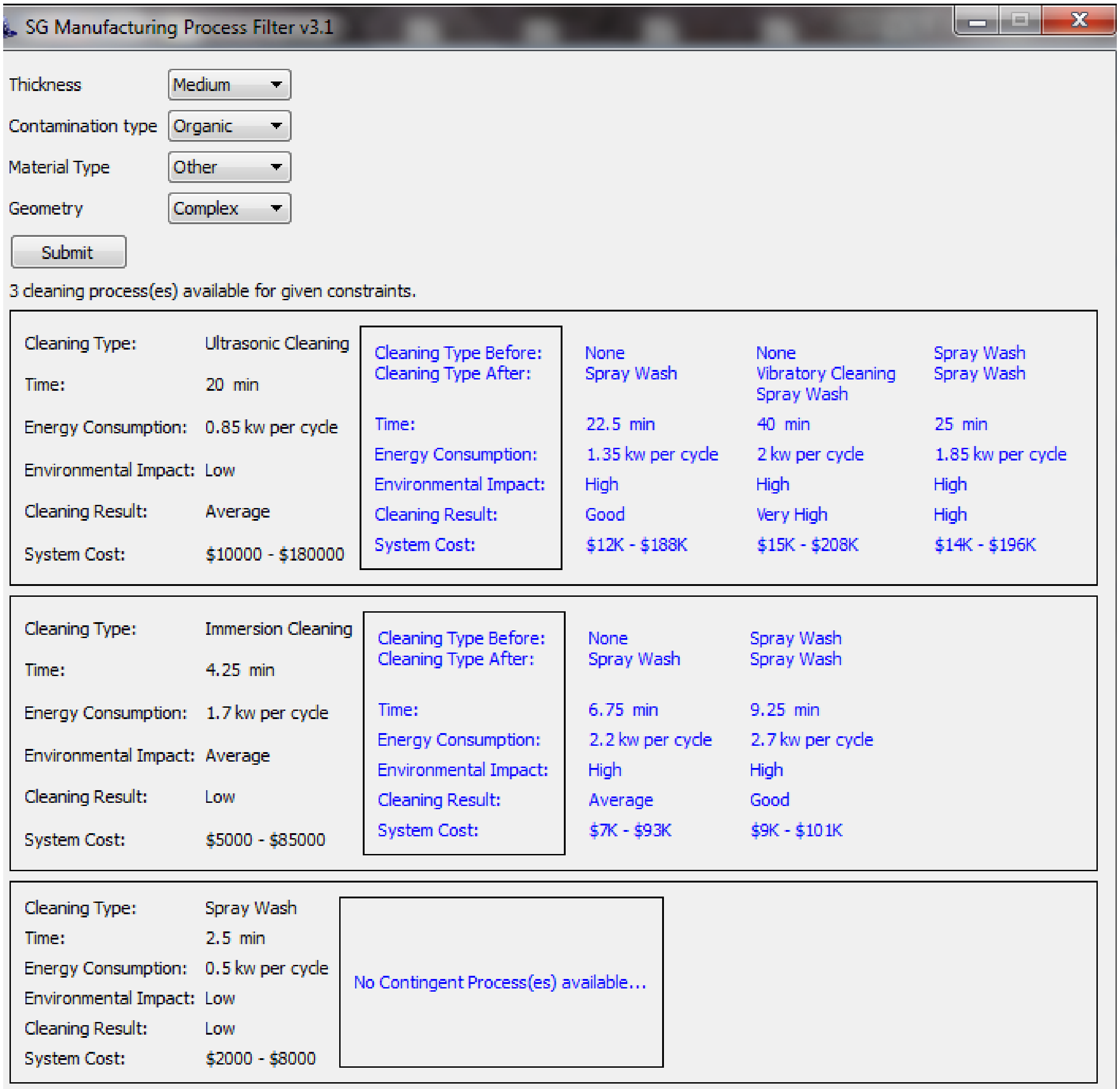
Cleaning Type:	Thermal Cleaning
Time:	37.5 min
Energy Consumption:	4.5 kw per cycle
Environmental Impact:	High
Cleaning Result:	Low
System Cost:	$8000 - $54000

Cleaning Type Before:	None	Spray Wash
Cleaning Type After:	Spray Wash	Spray Wash
Time:	40 min	42.5 min
Energy Consumption:	5 kw per cycle	5.5 kw per cycle
Environmental Impact:	Low	Low
Cleaning Result:	Average	Average
System Cost:	$10K - $62K	$12K - $70K

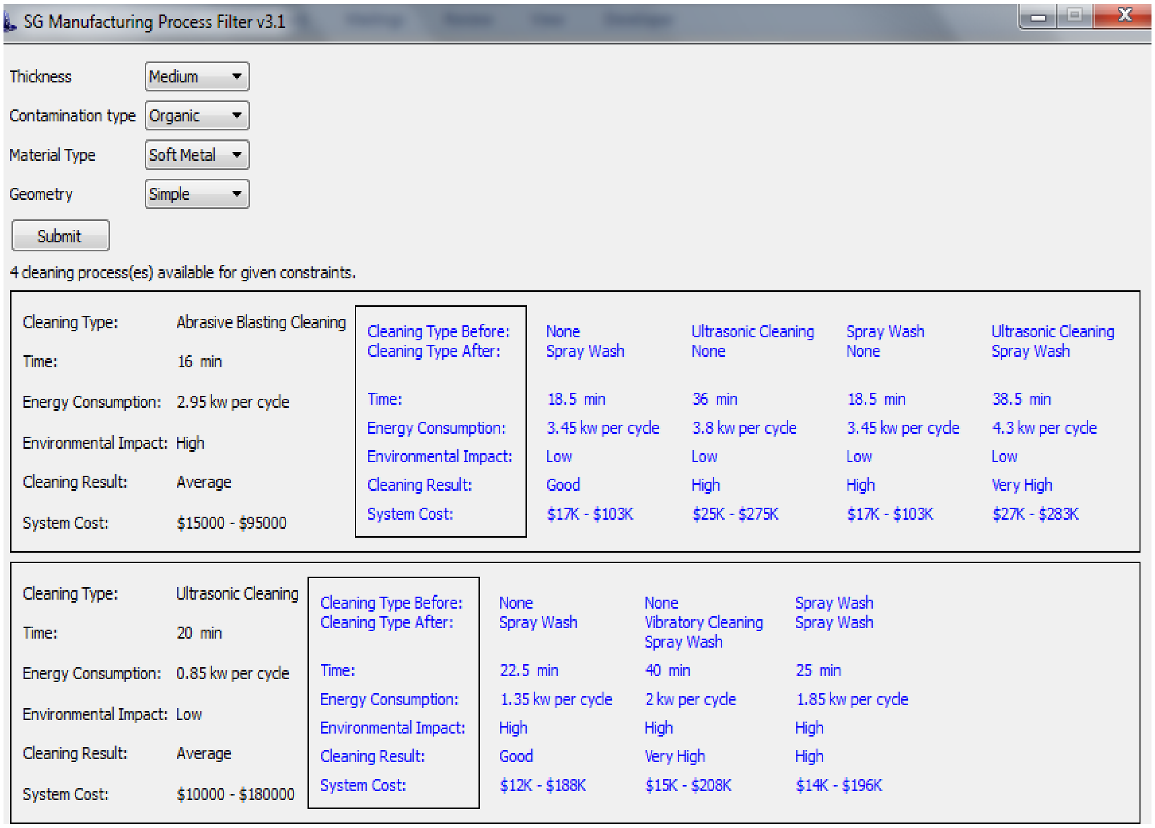
Cleaning Type:	Spray Wash
Time:	2.5 min
Energy Consumption:	0.5 kw per cycle
Environmental Impact:	Low
Cleaning Result:	Low
System Cost:	$2000 - $8000

No Contingent Process(es) available...

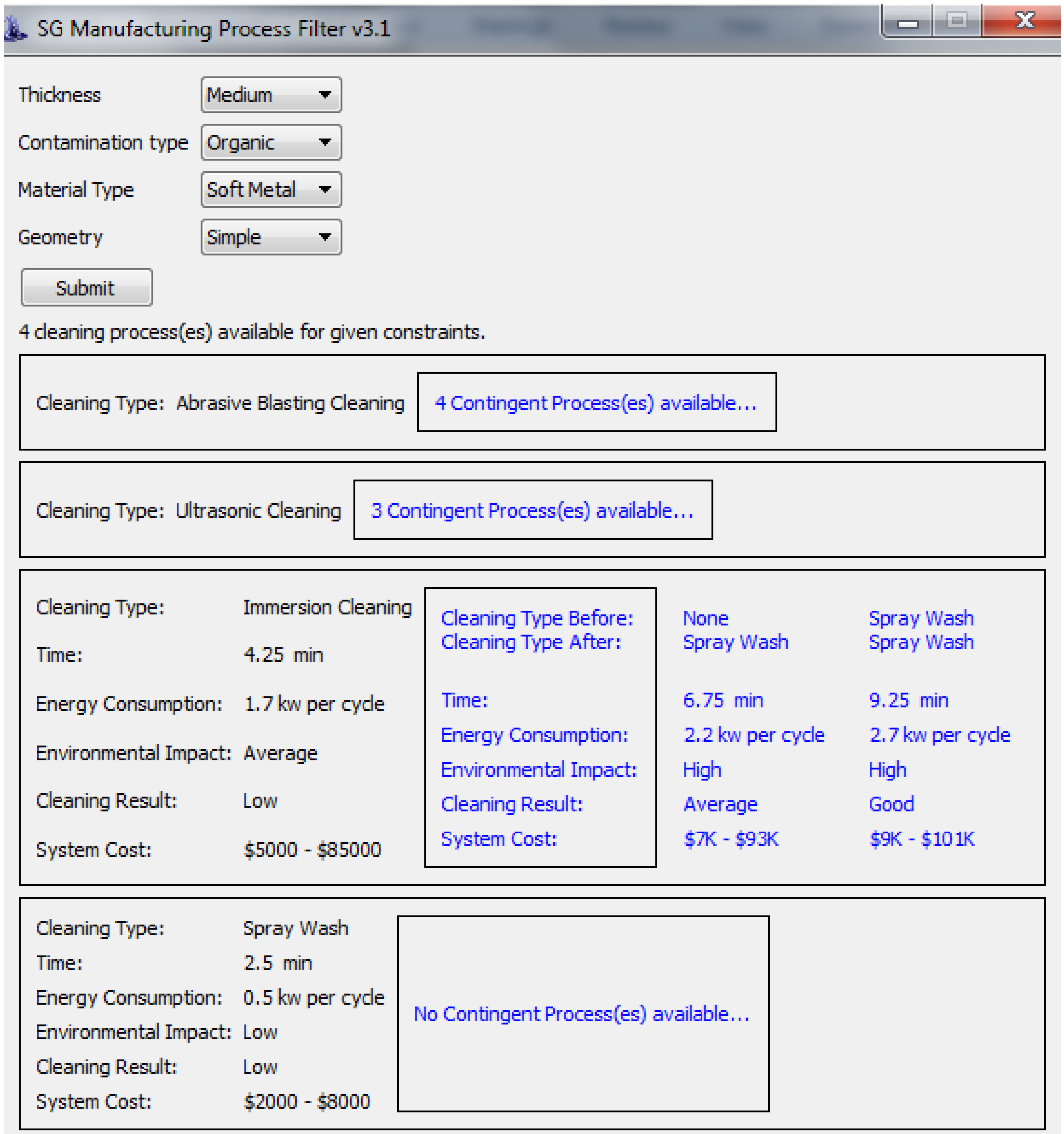
Result 15: Medium Organic Contamination Thickness, Other and Complex Part



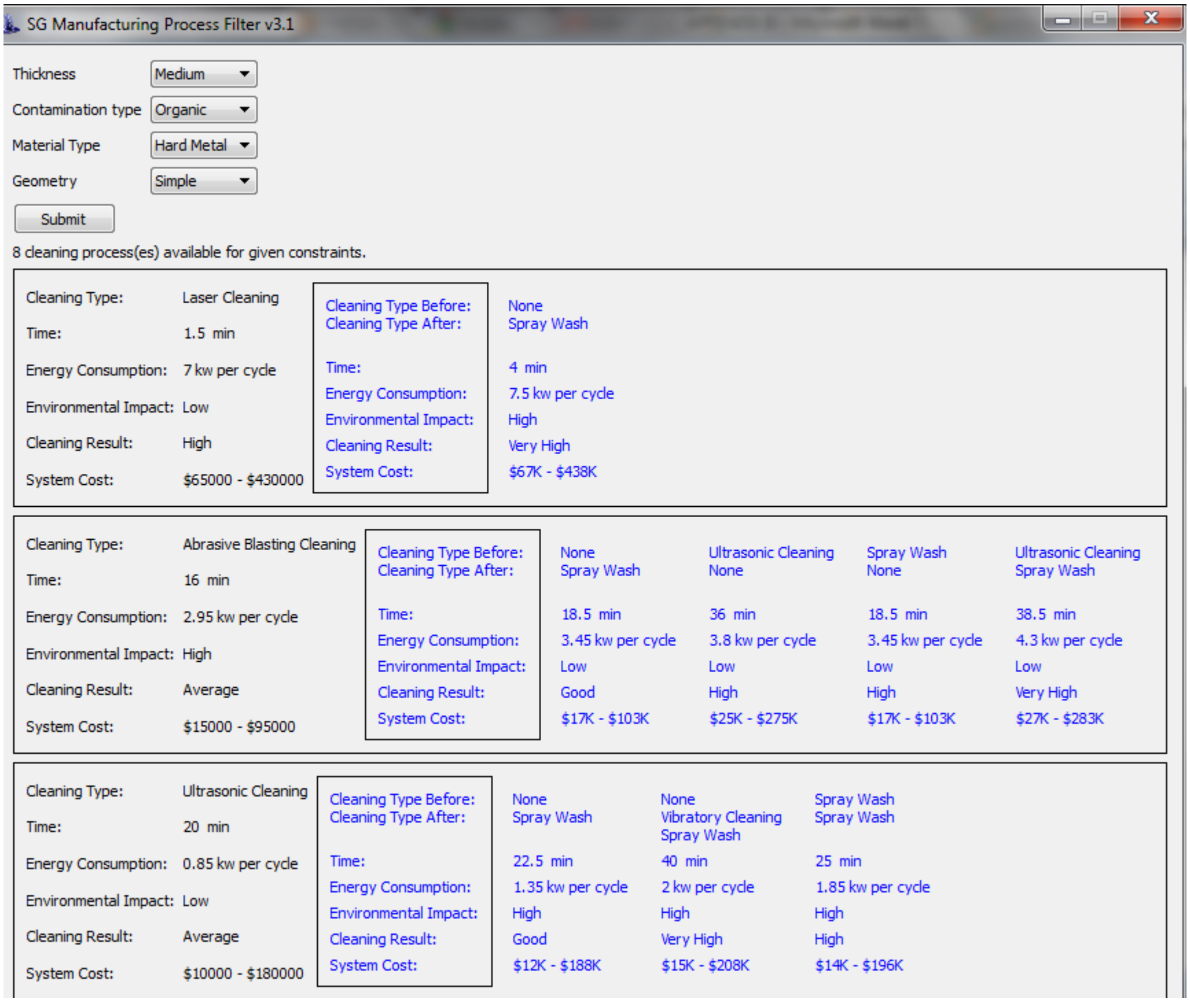
Result 16: Medium Organic Contamination Thickness, Soft Metal and Simple Part



Result 17: Medium Organic Contamination Thickness, Soft Metal and Simple Part



Result 18: Medium Organic Contamination Thickness, Hard Metal and Complex Part



Cleaning Type:	Molten Salt Cleaning
Time:	20 min
Energy Consumption:	3.75 kw per cycle
Environmental Impact:	High
Cleaning Result:	Average
System Cost:	$9000 - $60000

Cleaning Type Before:	None
Cleaning Type After:	Spray Wash
Time:	22.5 min
Energy Consumption:	4.25 kw per cycle
Environmental Impact:	Average
Cleaning Result:	Very High
System Cost:	$11K - $68K

Cleaning Type:	Immersion Cleaning
Time:	4.25 min
Energy Consumption:	1.7 kw per cycle
Environmental Impact:	Average
Cleaning Result:	Low
System Cost:	$5000 - $85000

Cleaning Type Before:	None	Spray Wash
Cleaning Type After:	Spray Wash	Spray Wash
Time:	6.75 min	9.25 min
Energy Consumption:	2.2 kw per cycle	2.7 kw per cycle
Environmental Impact:	High	High
Cleaning Result:	Average	Good
System Cost:	$7K - $93K	$9K - $101K

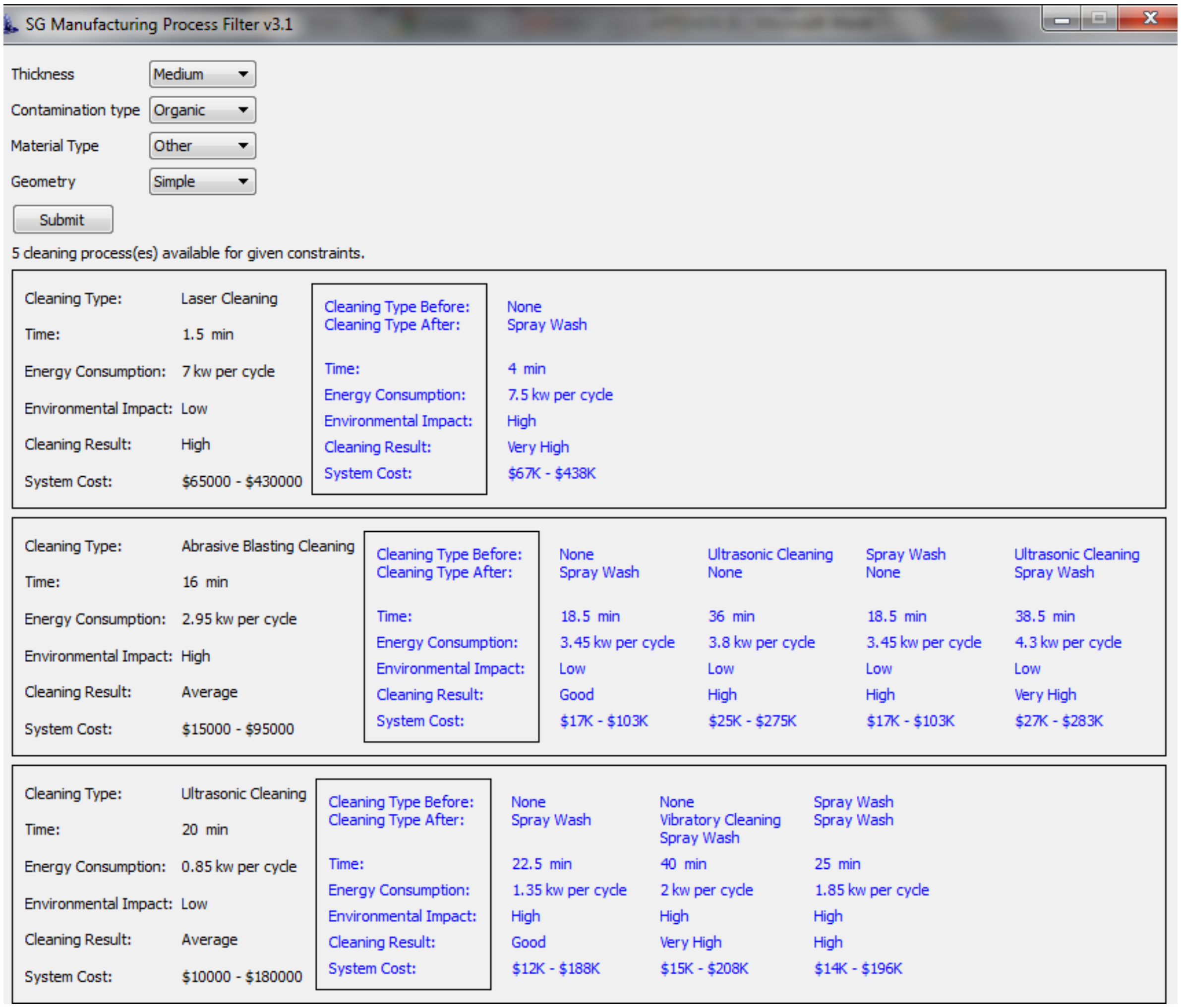
Cleaning Type:	Thermal Cleaning
Time:	37.5 min
Energy Consumption:	4.5 kw per cycle
Environmental Impact:	High
Cleaning Result:	Low
System Cost:	$8000 - $54000

Cleaning Type Before:	None	Spray Wash
Cleaning Type After:	Spray Wash	Spray Wash
Time:	40 min	42.5 min
Energy Consumption:	5 kw per cycle	5.5 kw per cycle
Environmental Impact:	Low	Low
Cleaning Result:	Average	Average
System Cost:	$10K - $62K	$12K - $70K

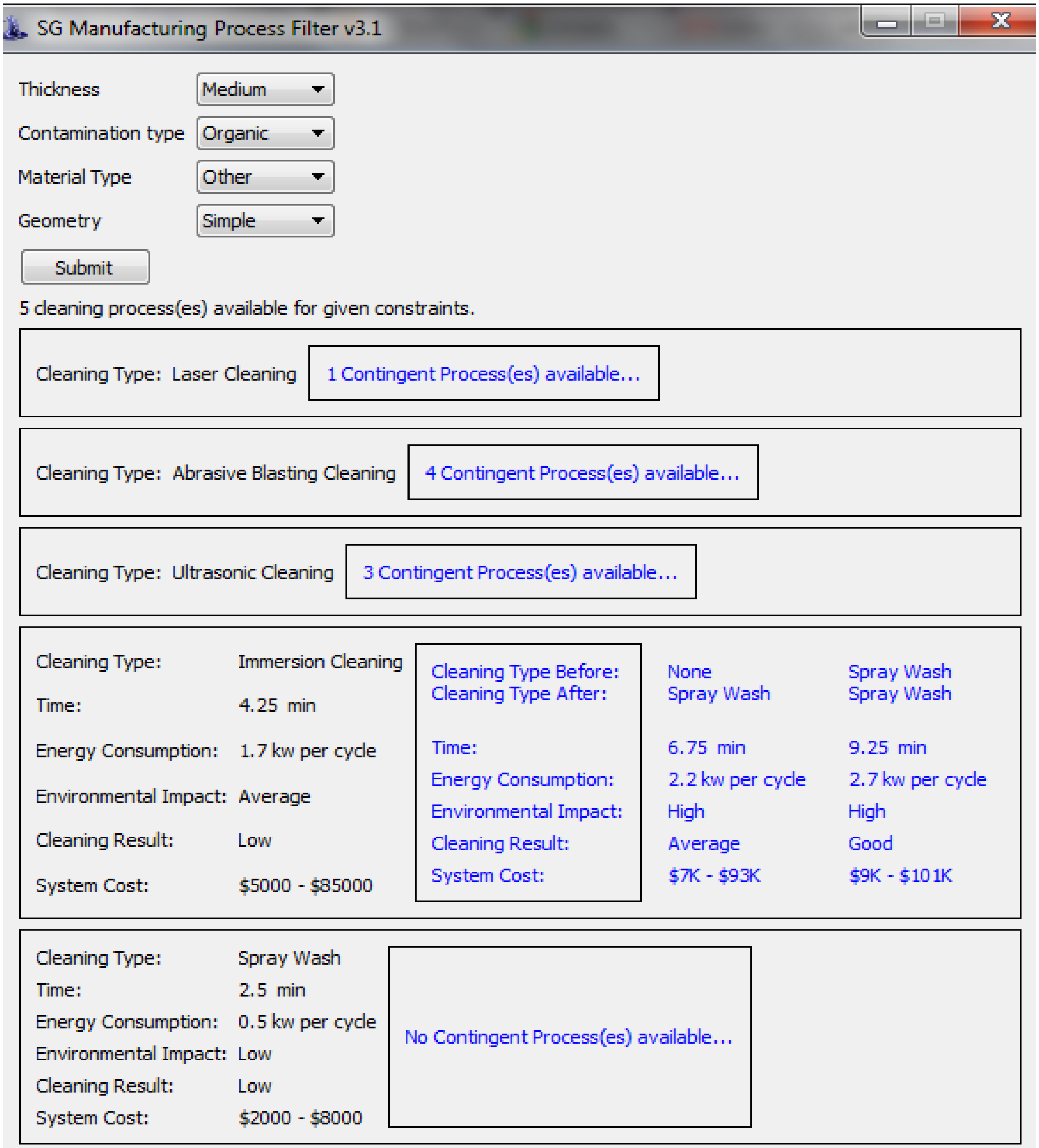
Cleaning Type:	Spray Wash
Time:	2.5 min
Energy Consumption:	0.5 kw per cycle
Environmental Impact:	Low
Cleaning Result:	Low
System Cost:	$2000 - $8000

No Contingent Process(es) available...

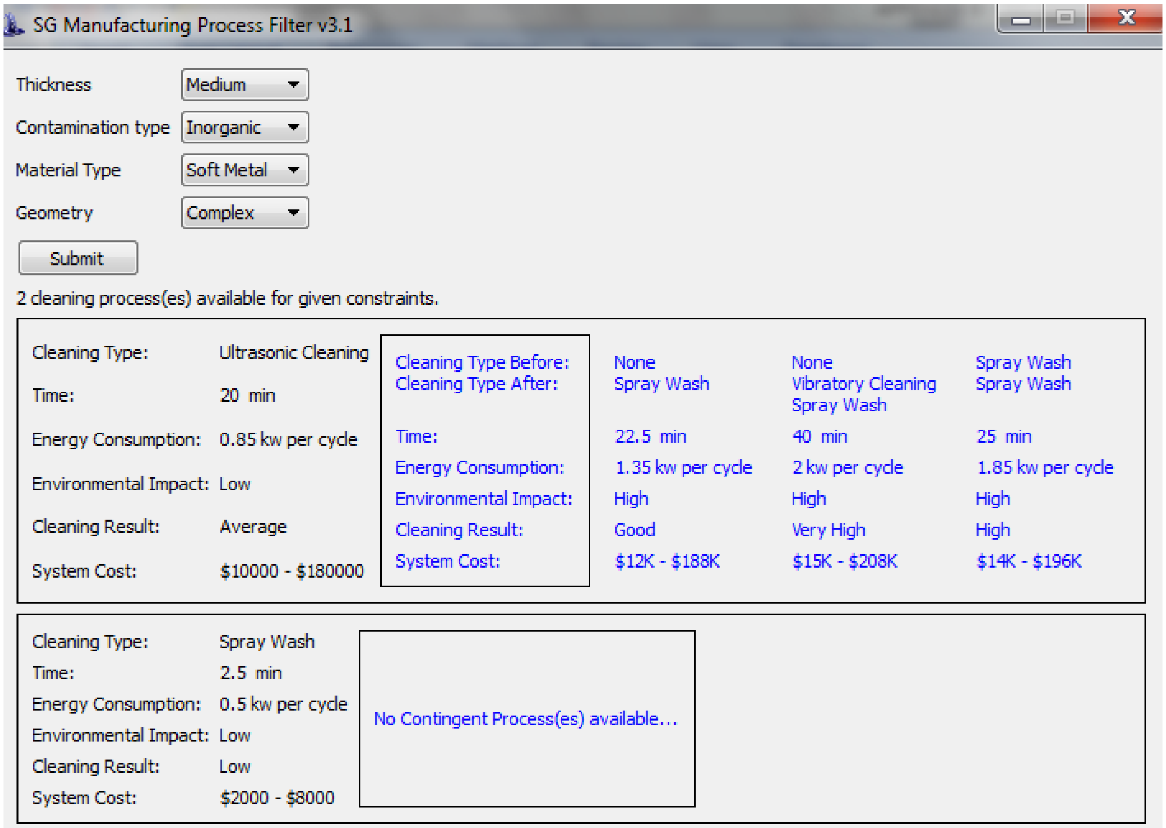
Result 19: Medium Organic Contamination Thickness, Other and Complex Part



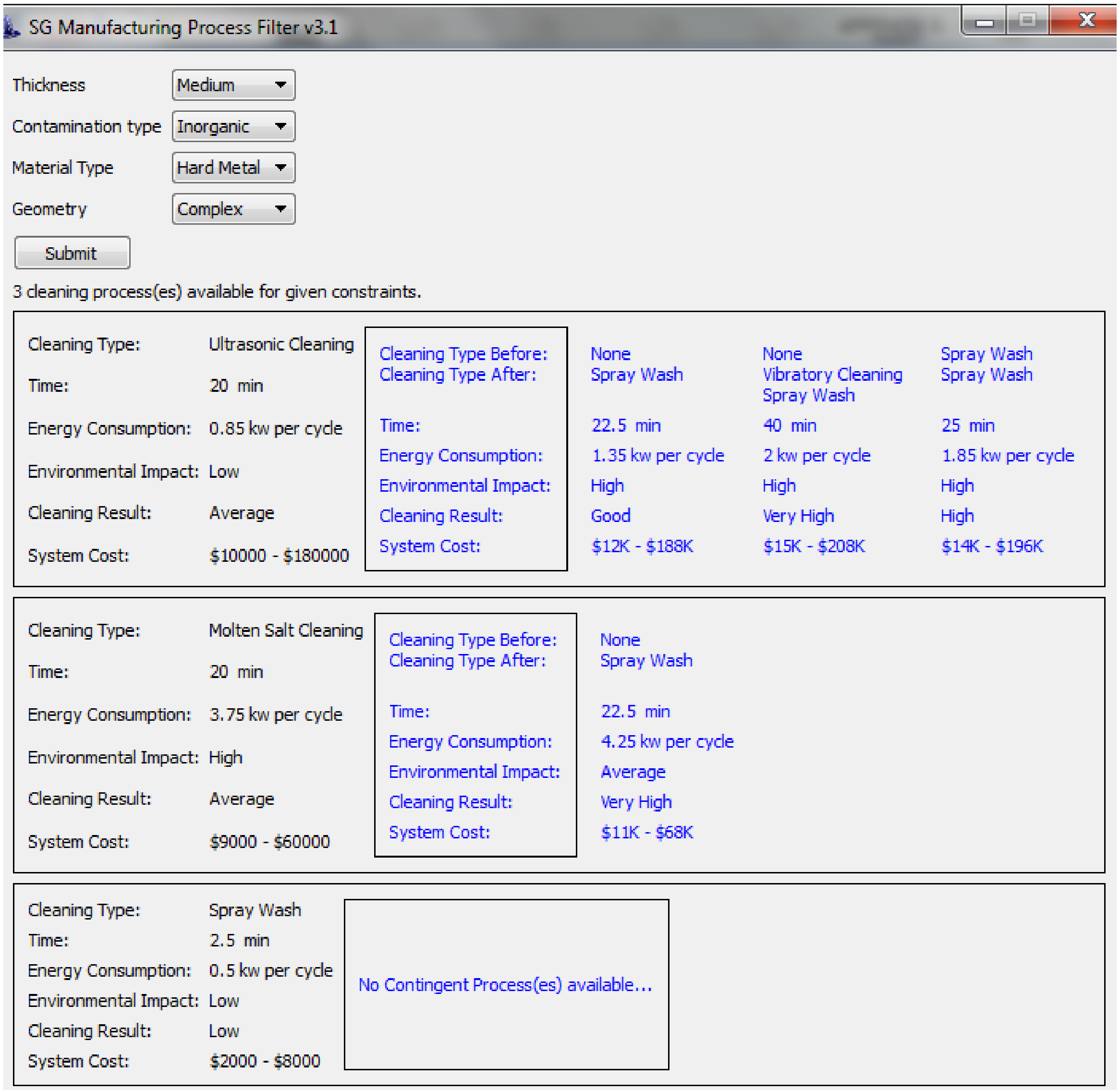
Result 20: Medium Organic Contamination Thickness, Other and Simple Part



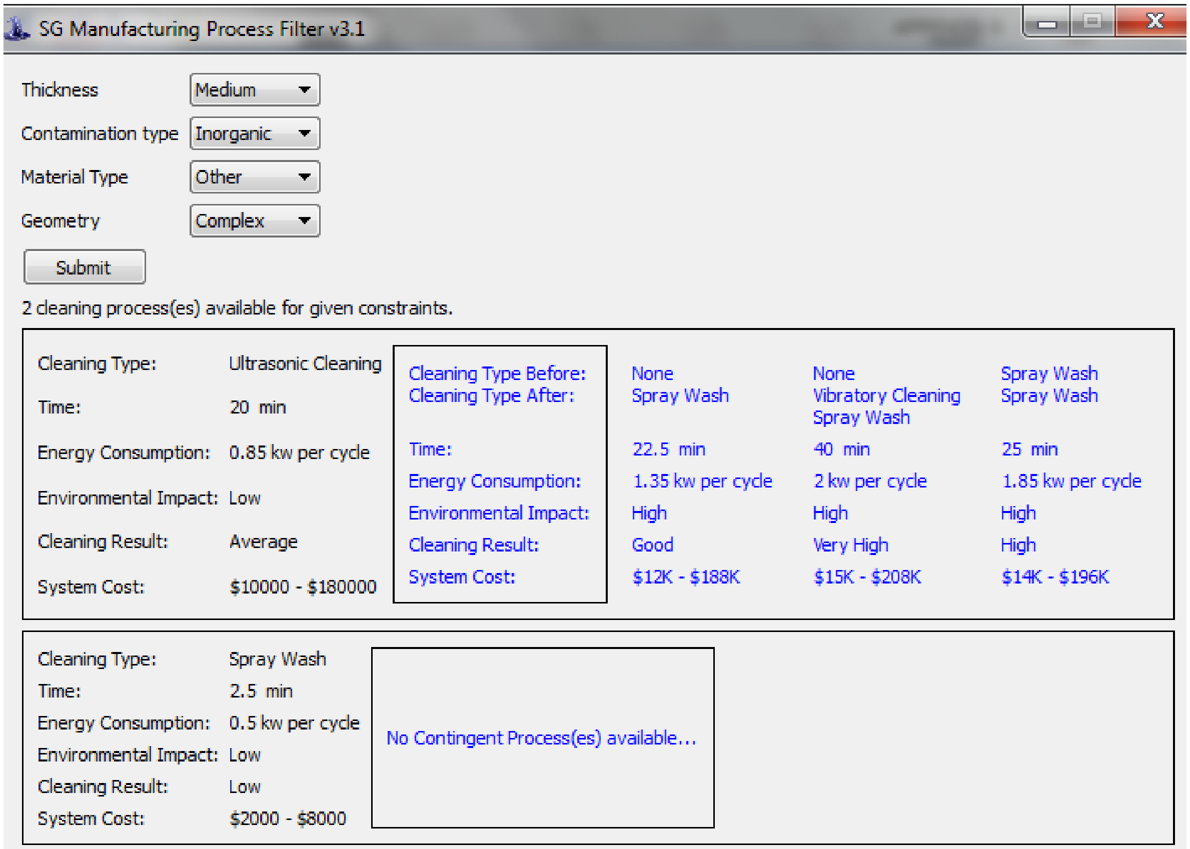
Result 21: Medium Inorganic Contamination Thickness, Soft Metal and Complex Part



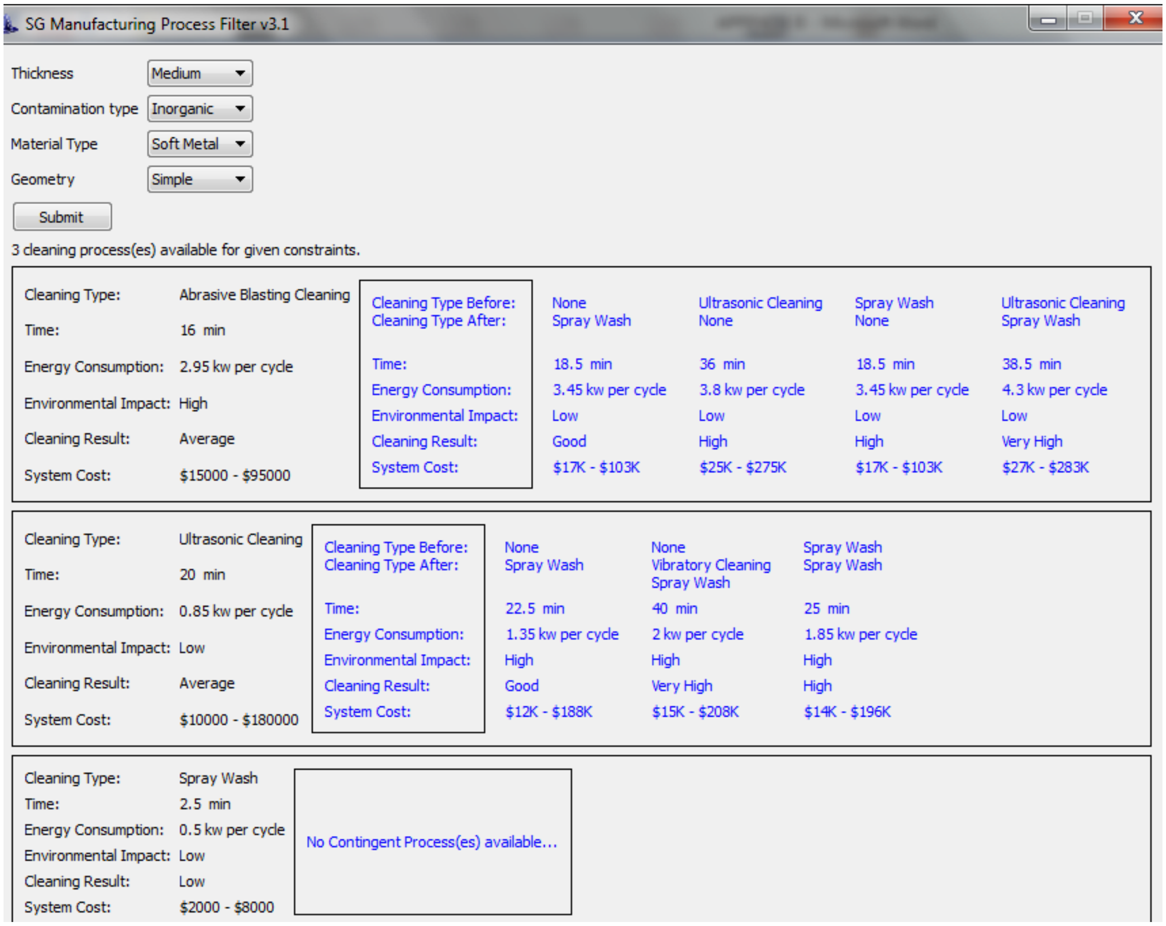
Result 22: Medium Inorganic Contamination Thickness, Hard Metal and Complex Part



Result 23: Medium Inorganic Contamination Thickness, Other and Complex Part



Result 24: Medium Inorganic Contamination Thickness, Soft Metal and Simple Par



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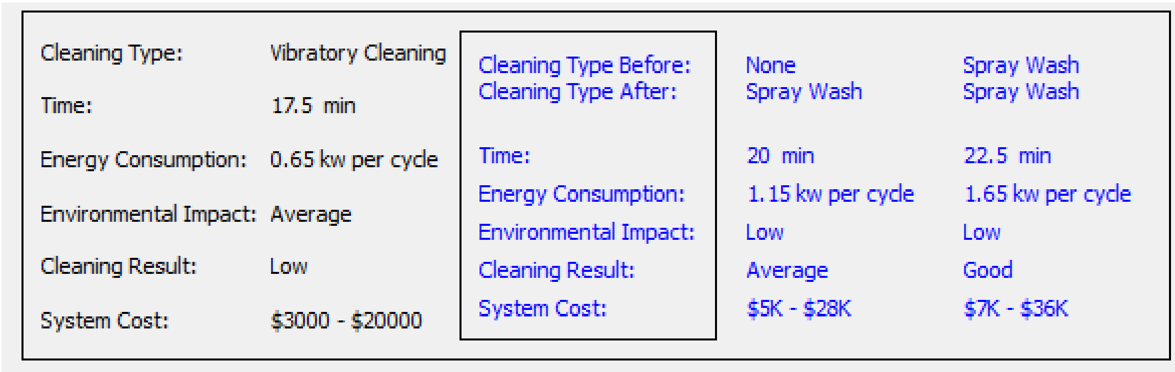
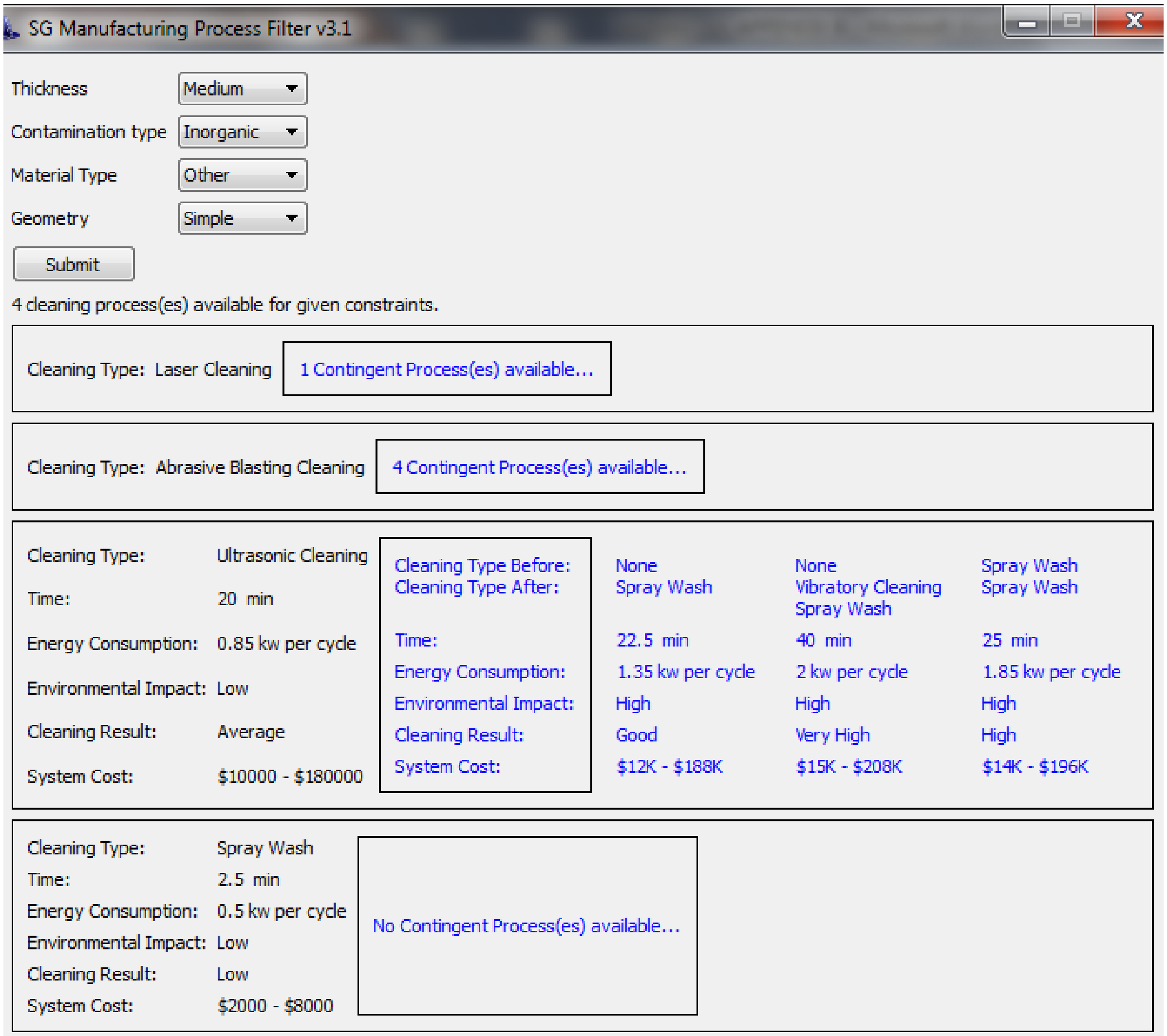
Result 25: Medium Inorganic Contamination Thickness, Hard Metal and Complex Part

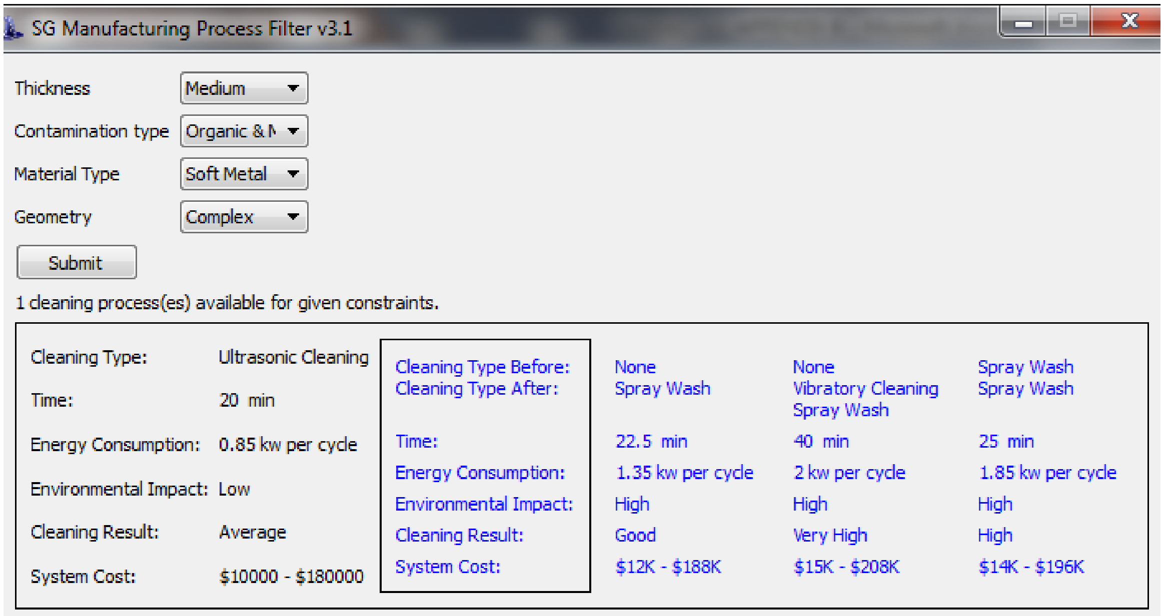


Result 26: Medium Inorganic Contamination Thickness, Other and Simple Part

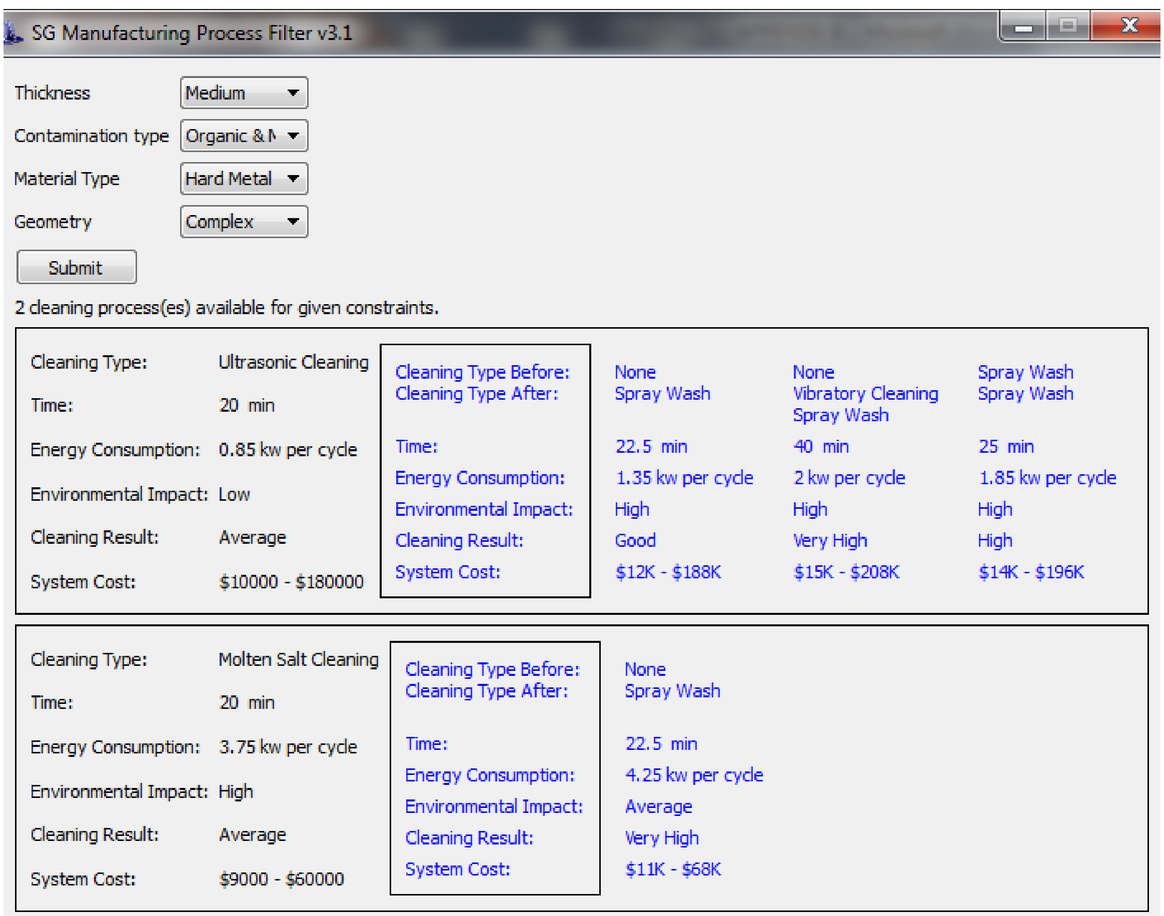
Result 27: Medium Inorganic Contamination Thickness, Other and Simple Part



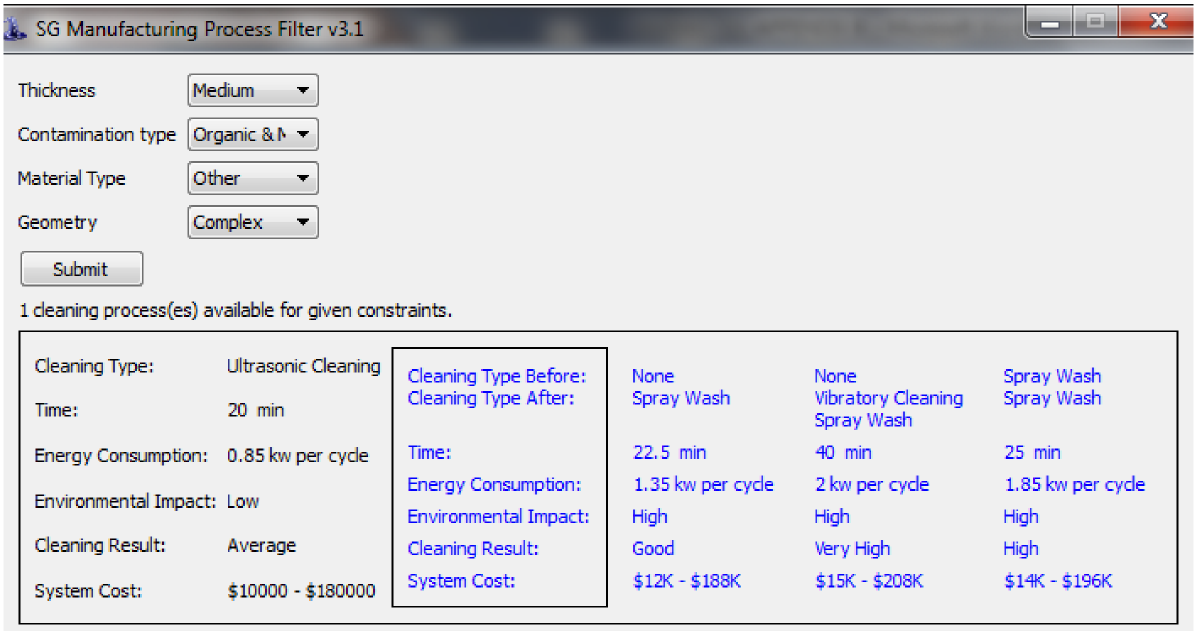
Result 28: Medium Organic & Mix Contamination Thickness, Soft Metal and Complex Part



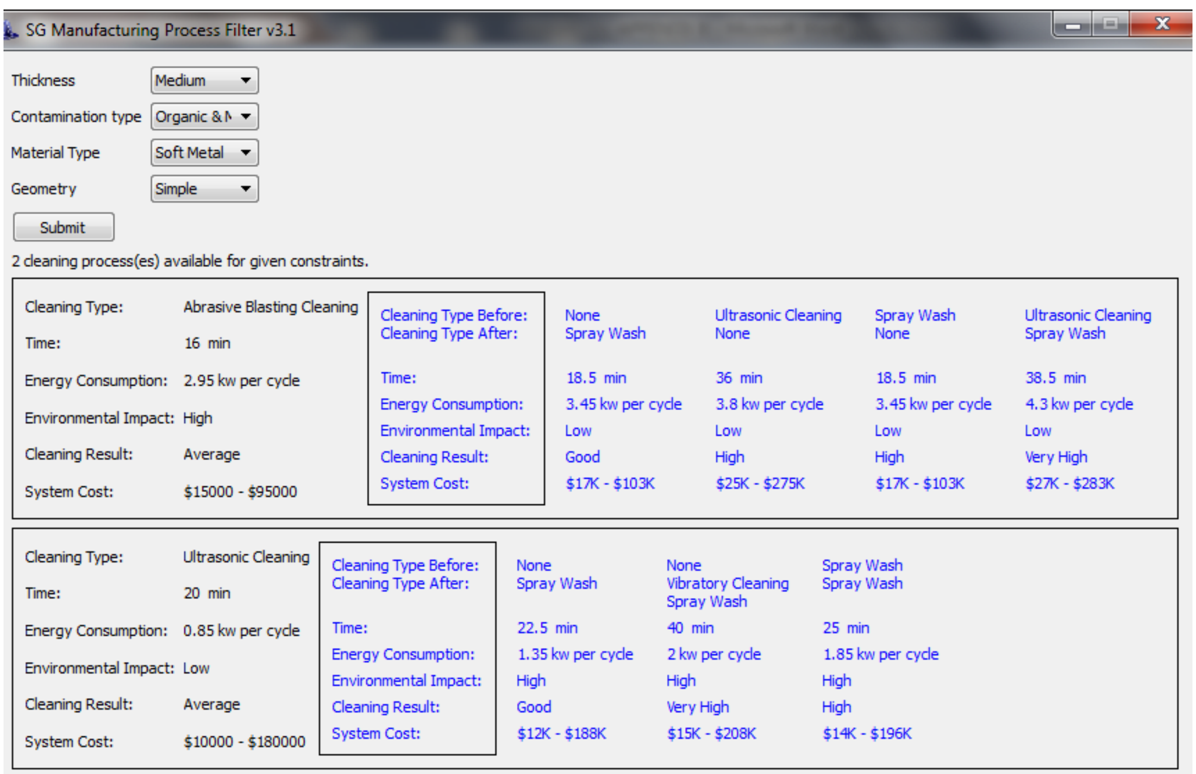
Result 29: Medium Organic & Mix Contamination Thickness, Hard Metal and Complex Part



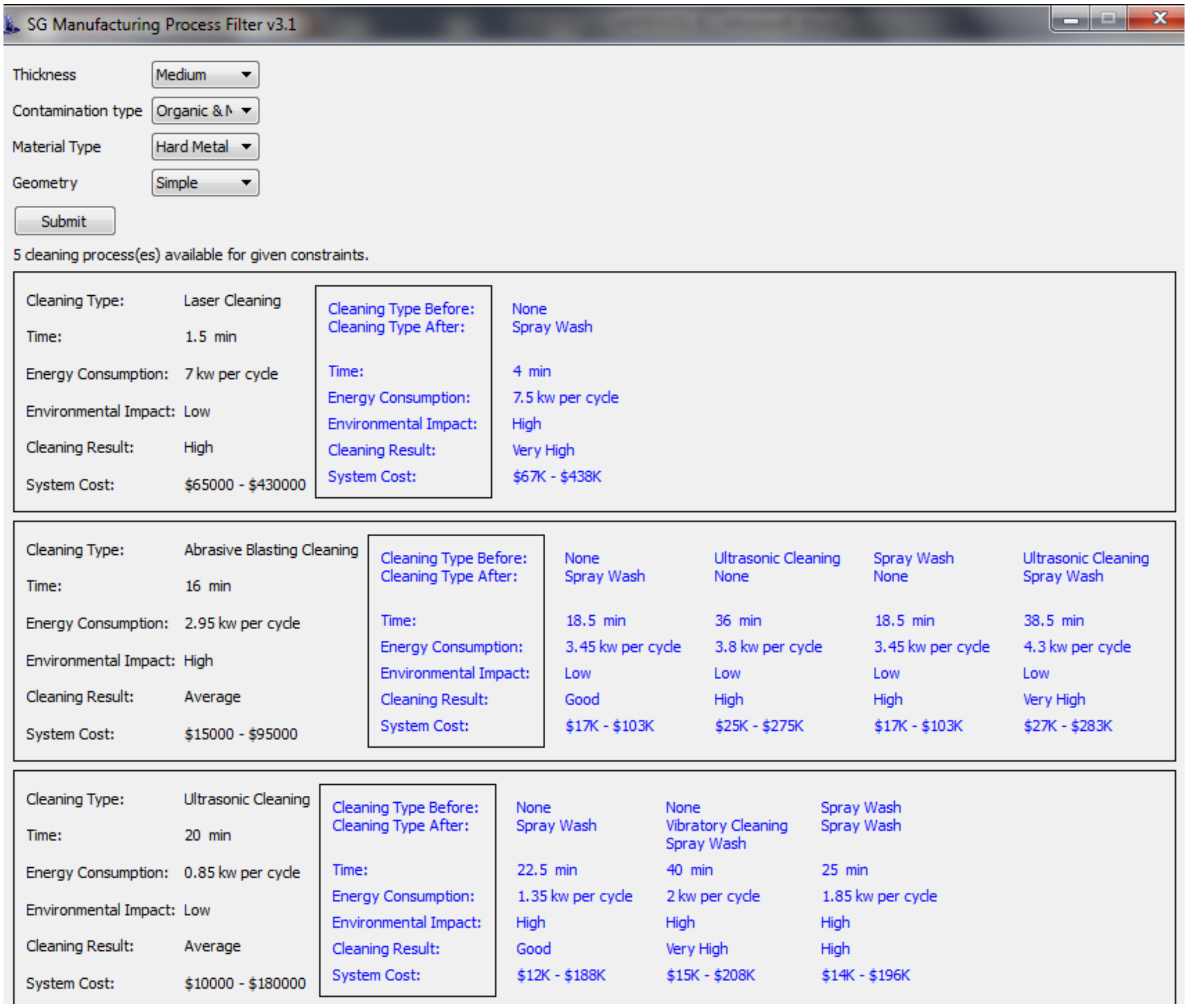
Result 30: Medium Organic & Mix Contamination Thickness, Other and Complex Part



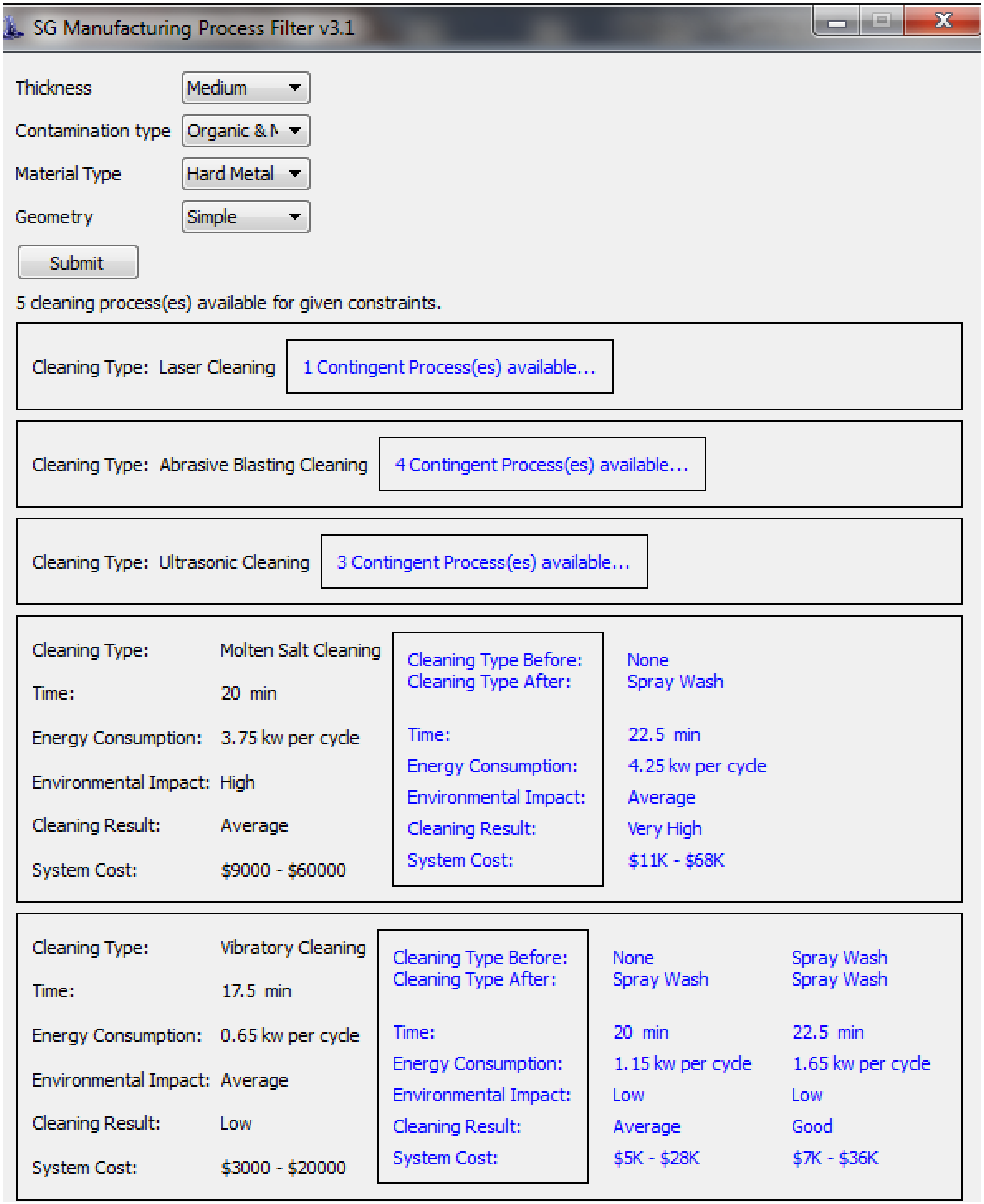
Result 31: Medium Organic & Mix Contamination Thickness, Soft Metal and Simple Part



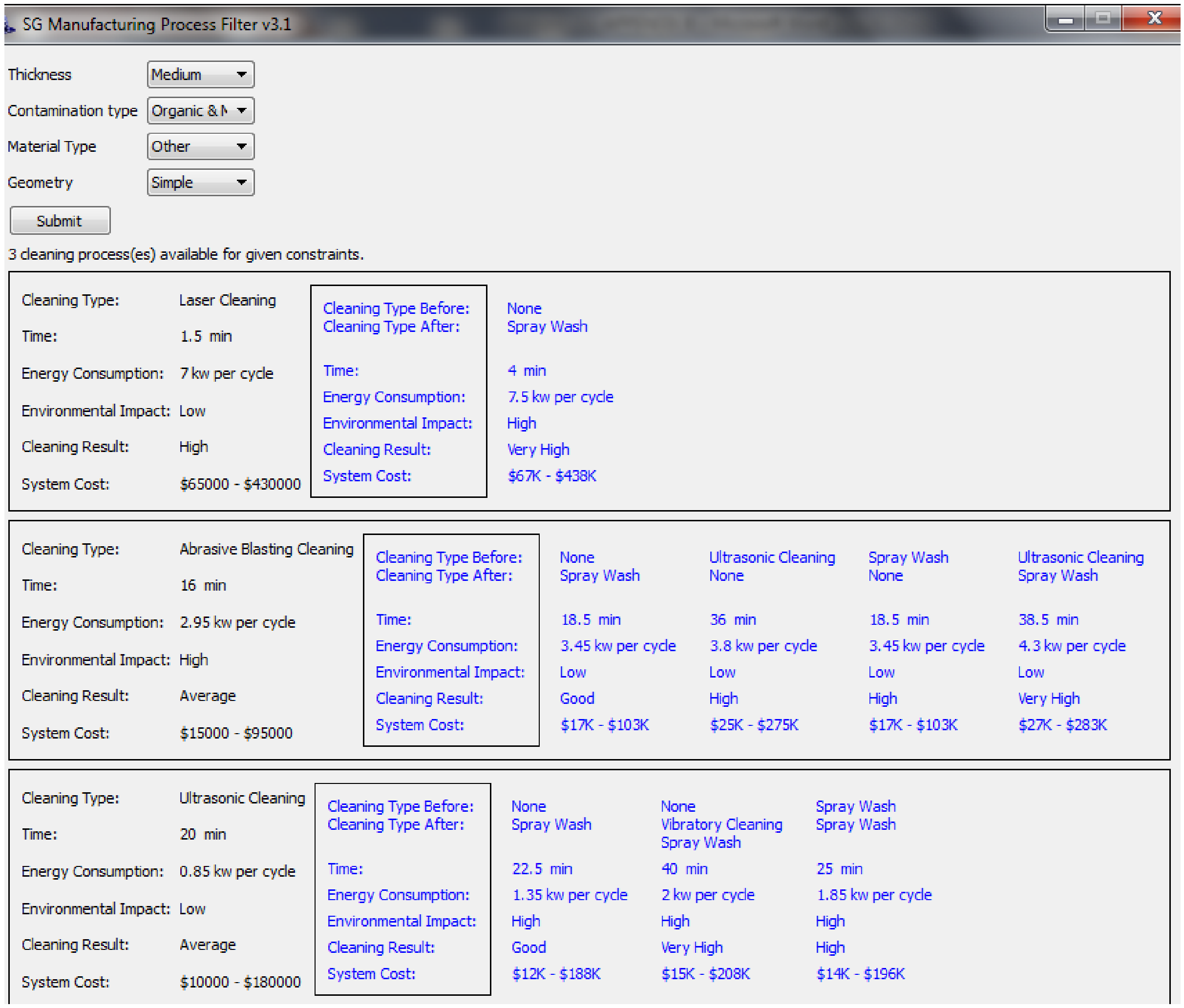
Result 32: Medium Organic & Mix Contamination Thickness, Hard Metal and Simple Part



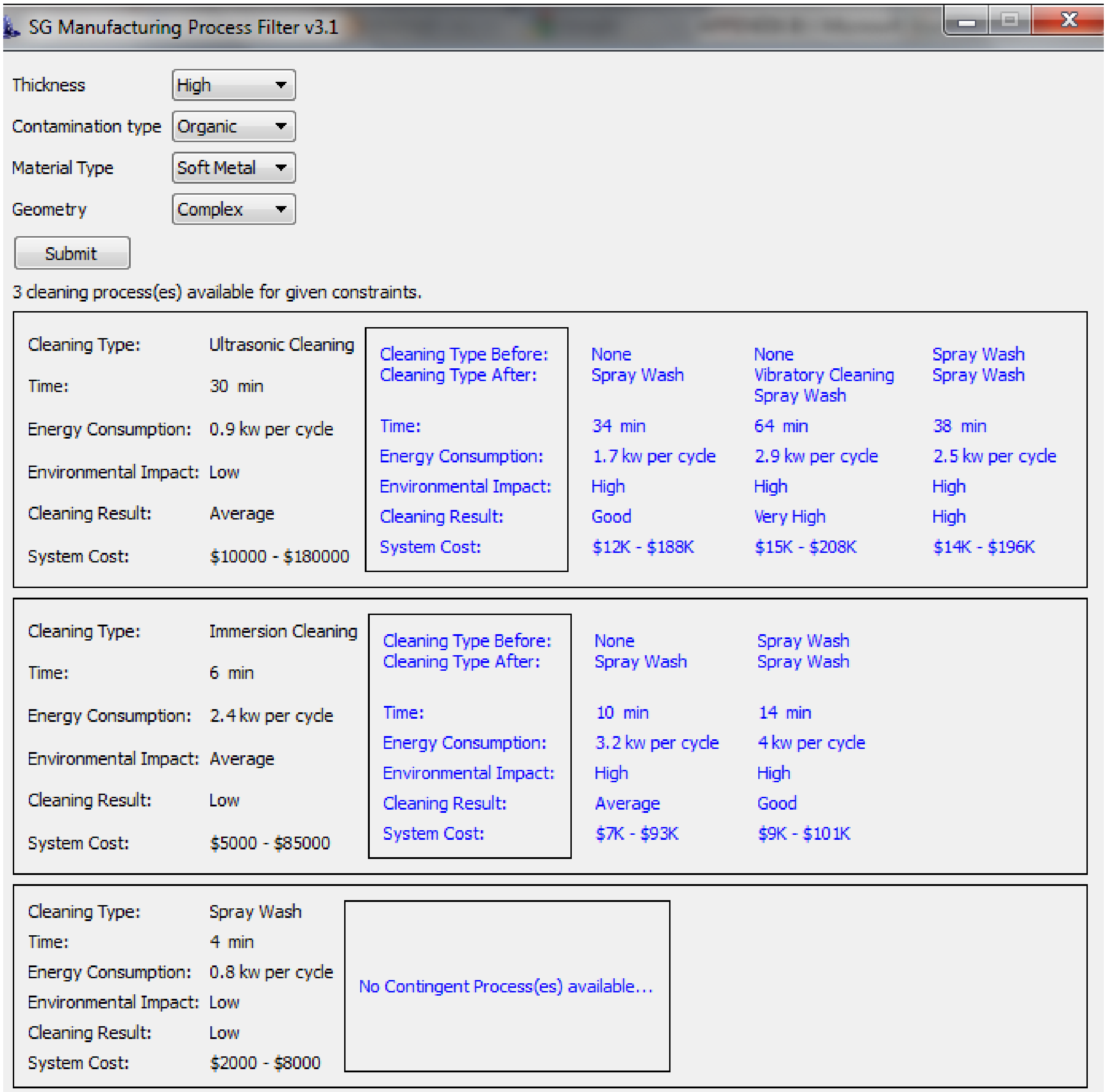
Result 33: Medium Organic & Mix Contamination Thickness, Hard Metal and Simple Part



Result 34: Medium Organic & Mix Contamination Thickness, Other and Simple Part

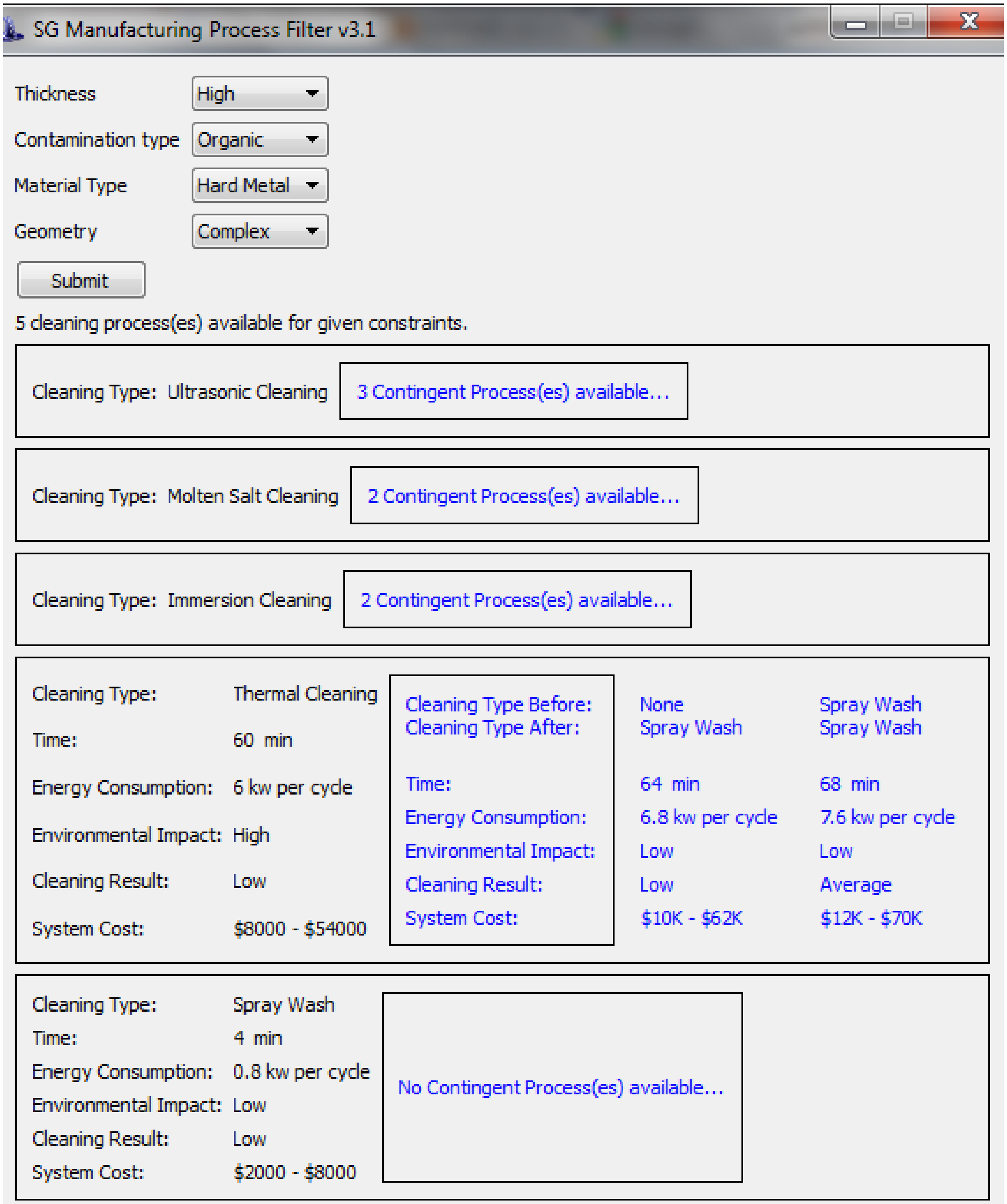


Result 35: High Organic Contamination Thickness, Soft Metal and Complex Part

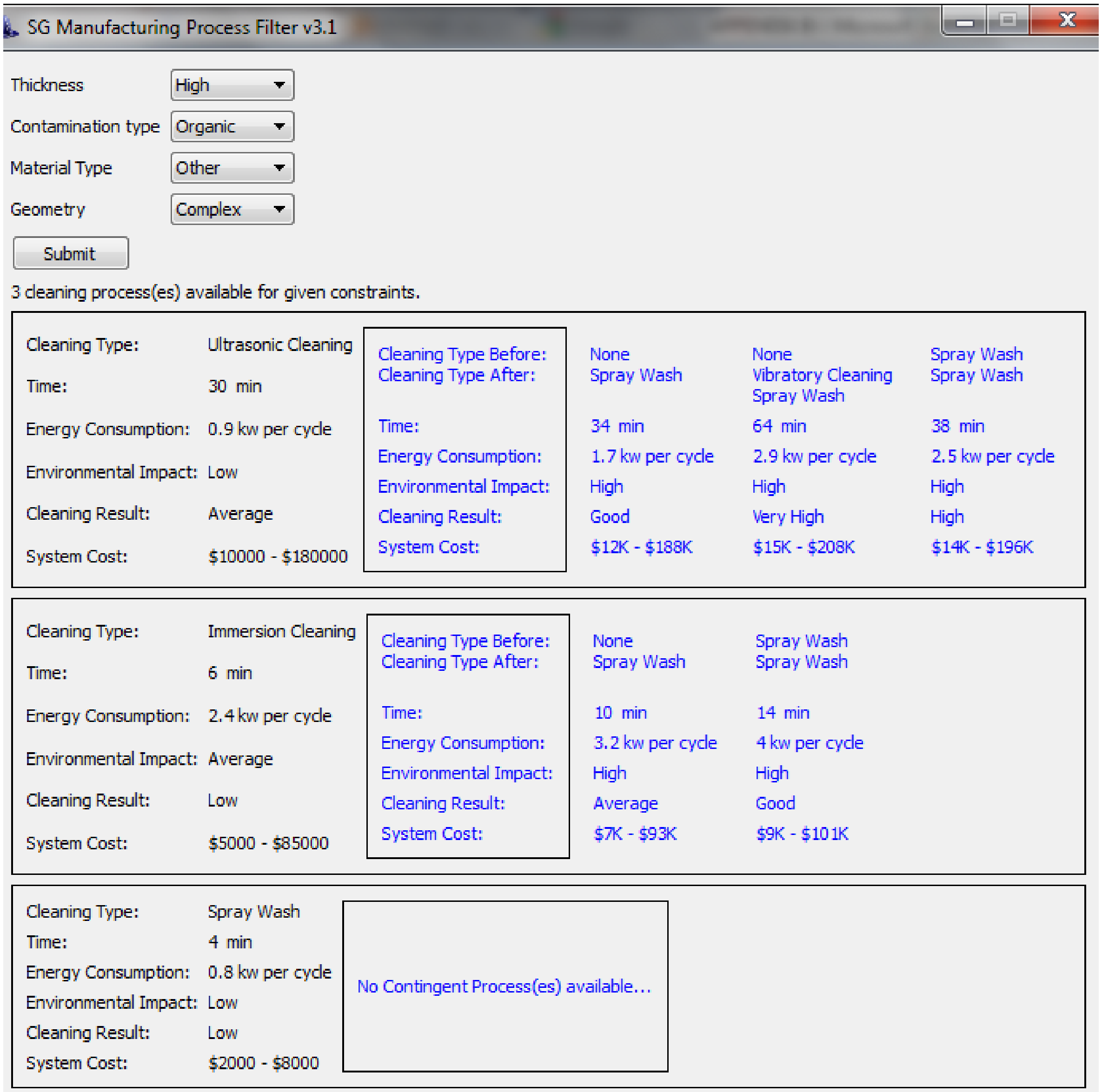


Result 36: High Organic Contamination Thickness, Hard Metal and Complex Part

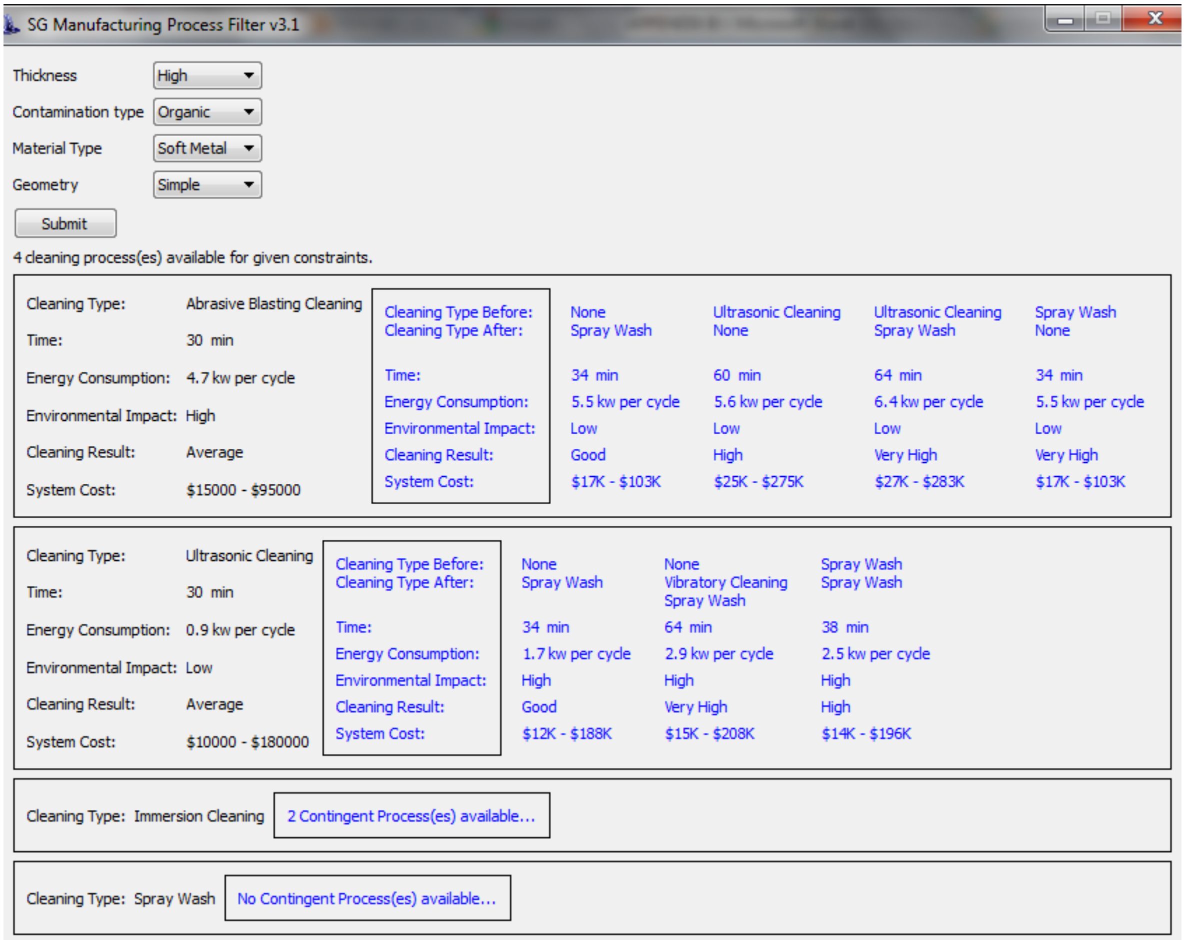
Result 37: High Organic Contamination Thickness, Hard Metal and Complex Part



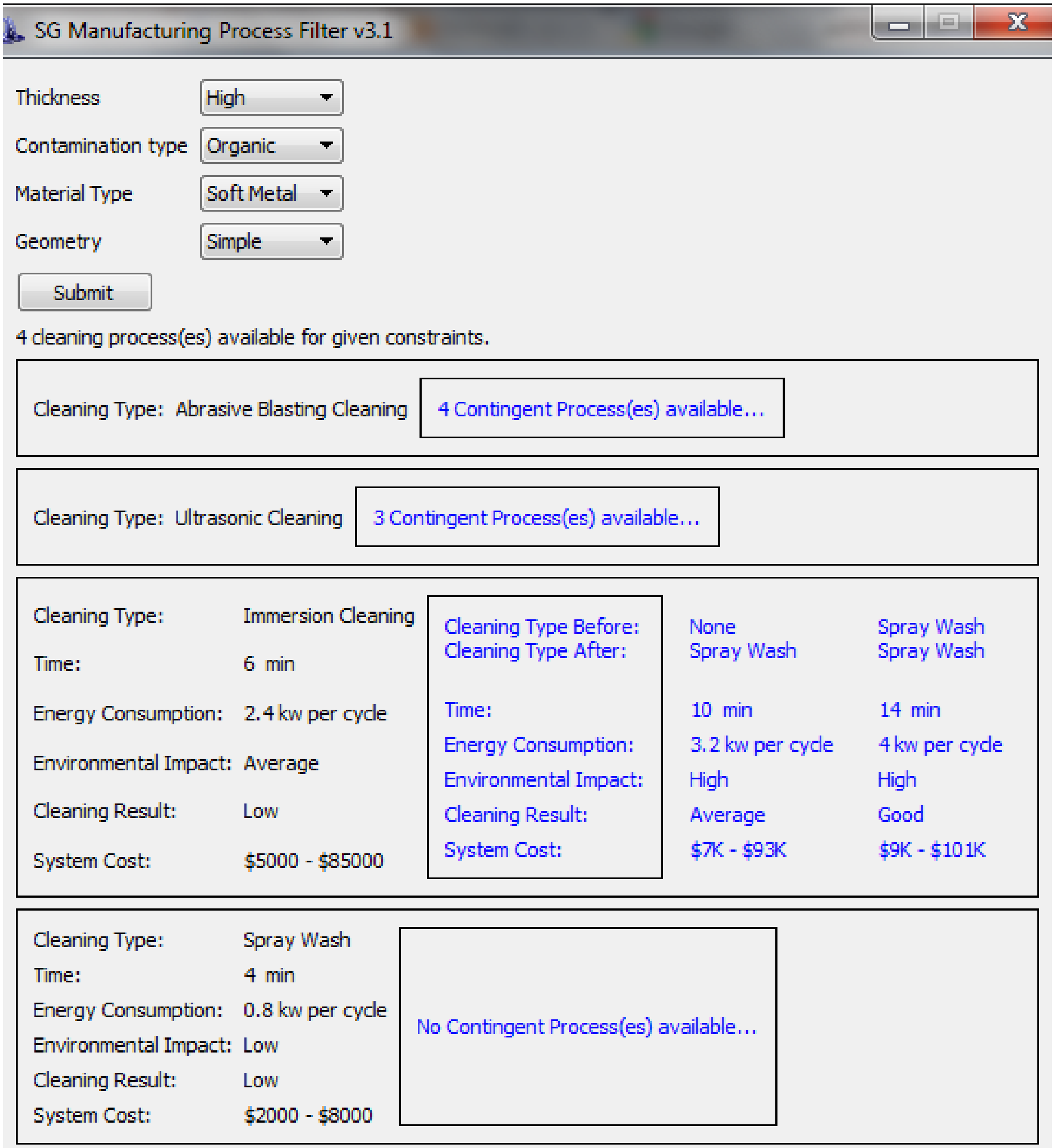
Result 38: High Organic Contamination Thickness, Other and Complex Part



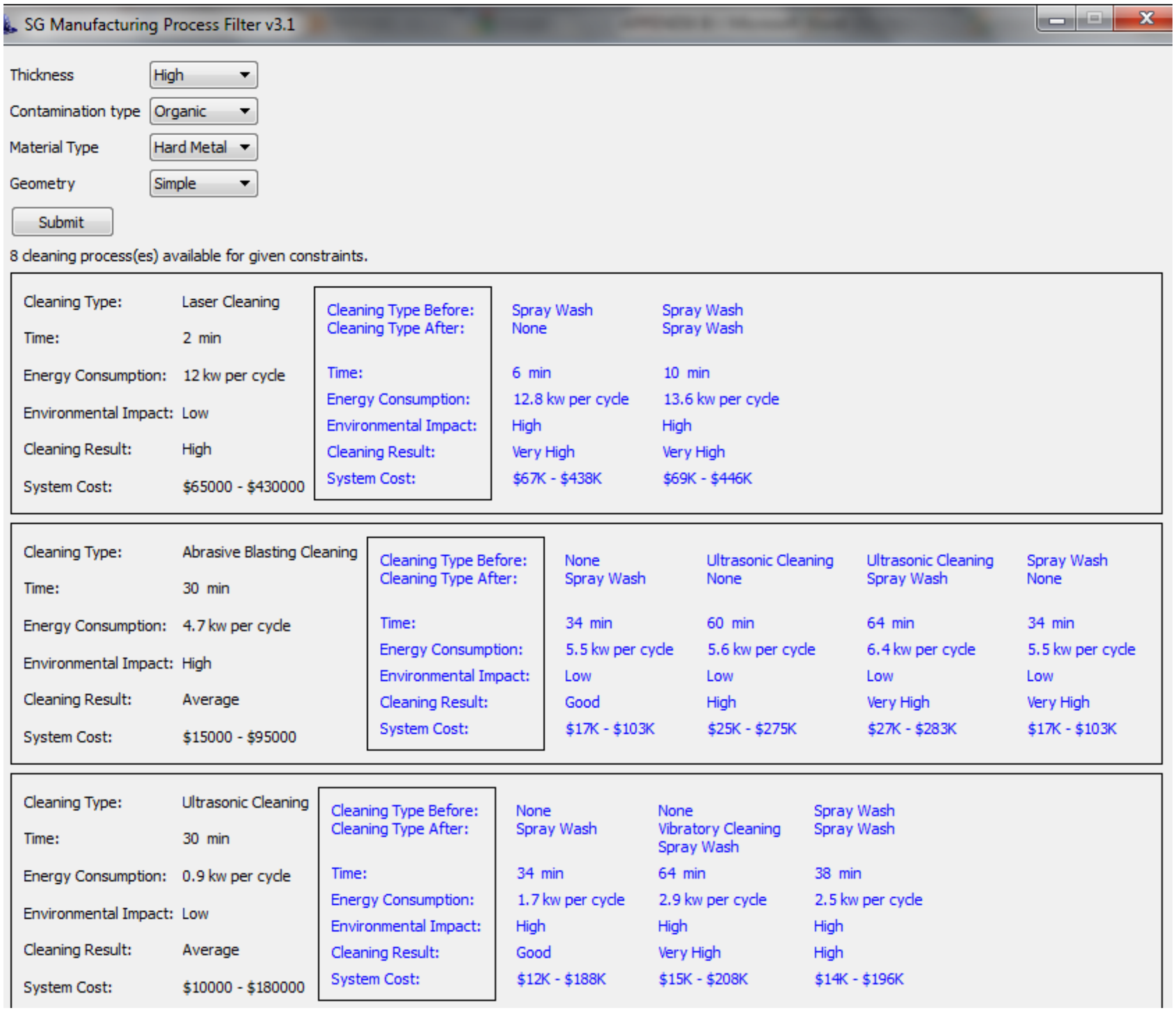
Result 39: High Organic Contamination Thickness, Soft Metal and Simple Part



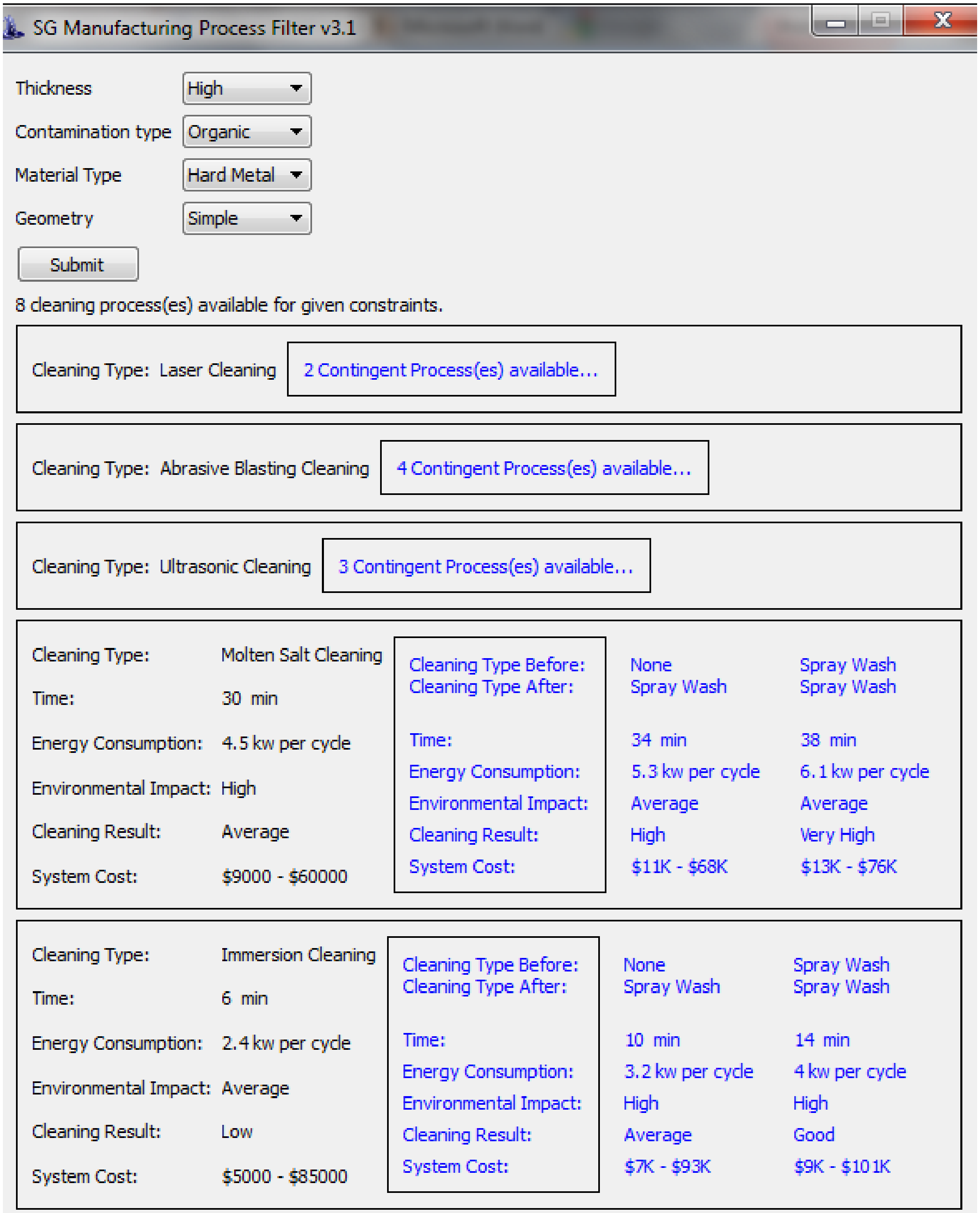
Result 40: High Organic Contamination Thickness, Soft Metal and Simple Part



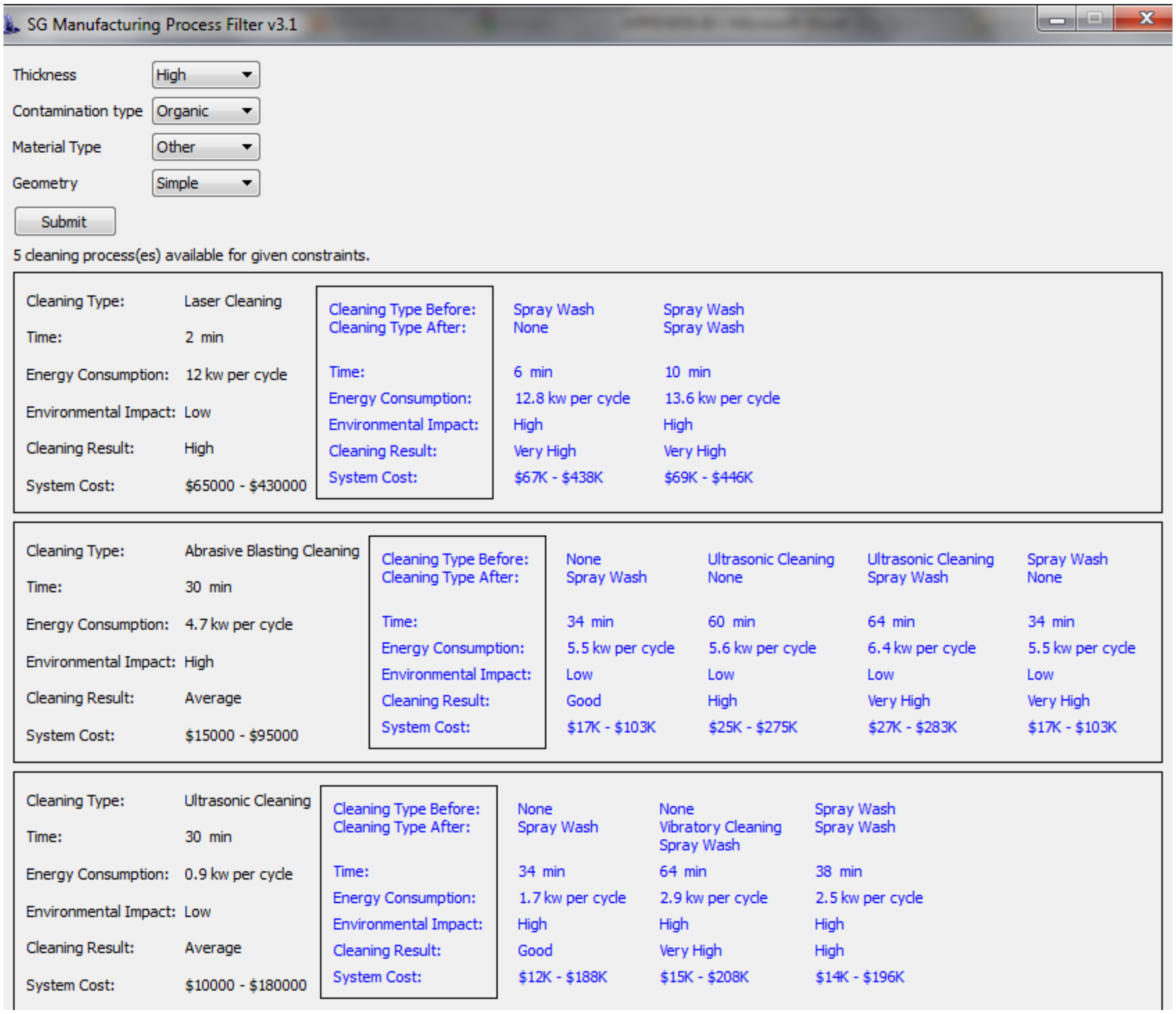
Result 41: High Organic Contamination Thickness, Hard Metal and Simple Part



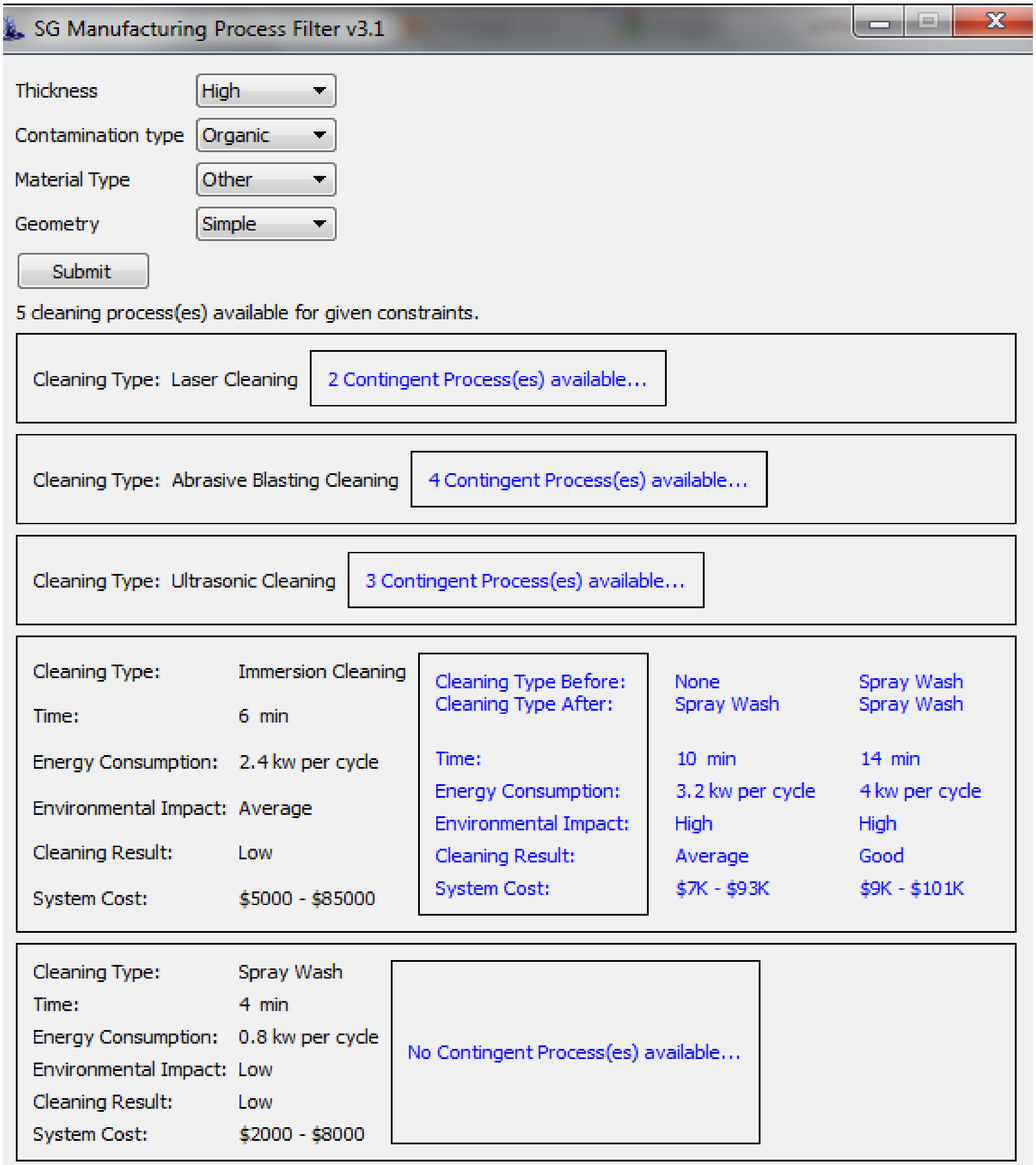
Result 42: High Organic Contamination Thickness, Hard Metal and Simple Part



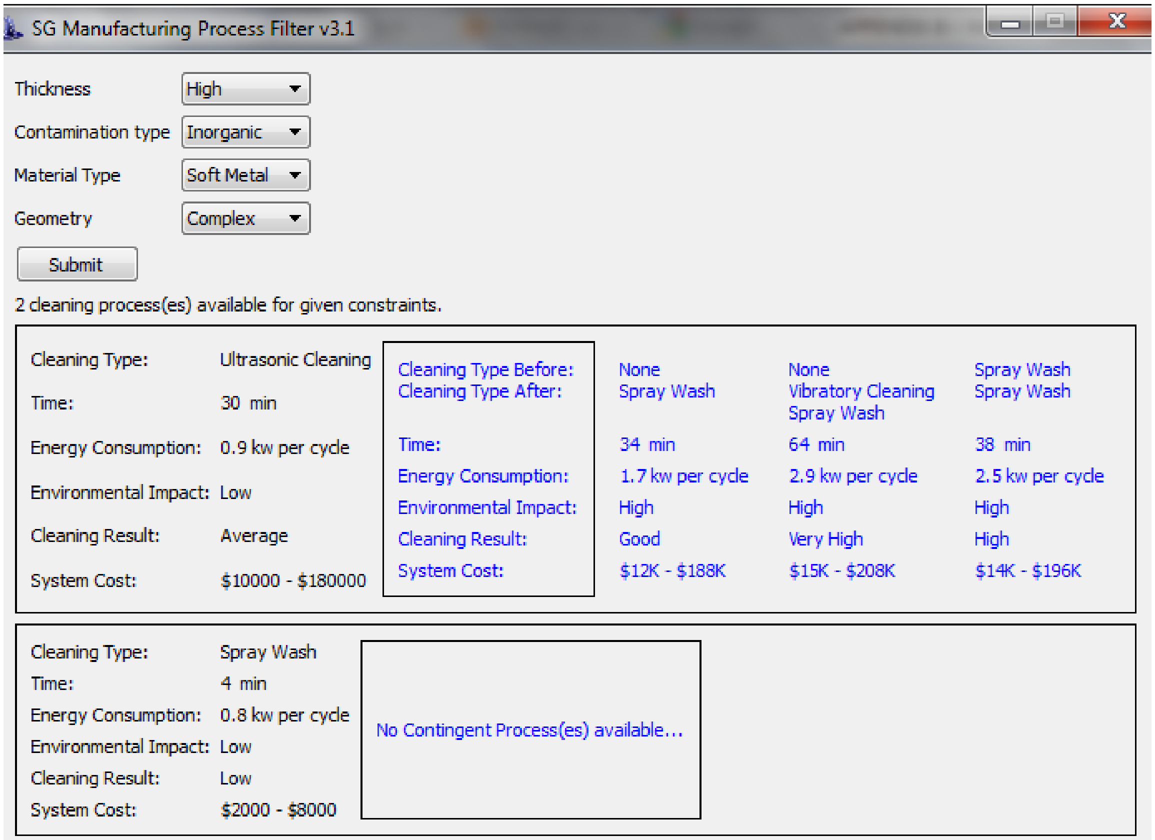
Result 43: High Organic Contamination Thickness, Other and Simple Part



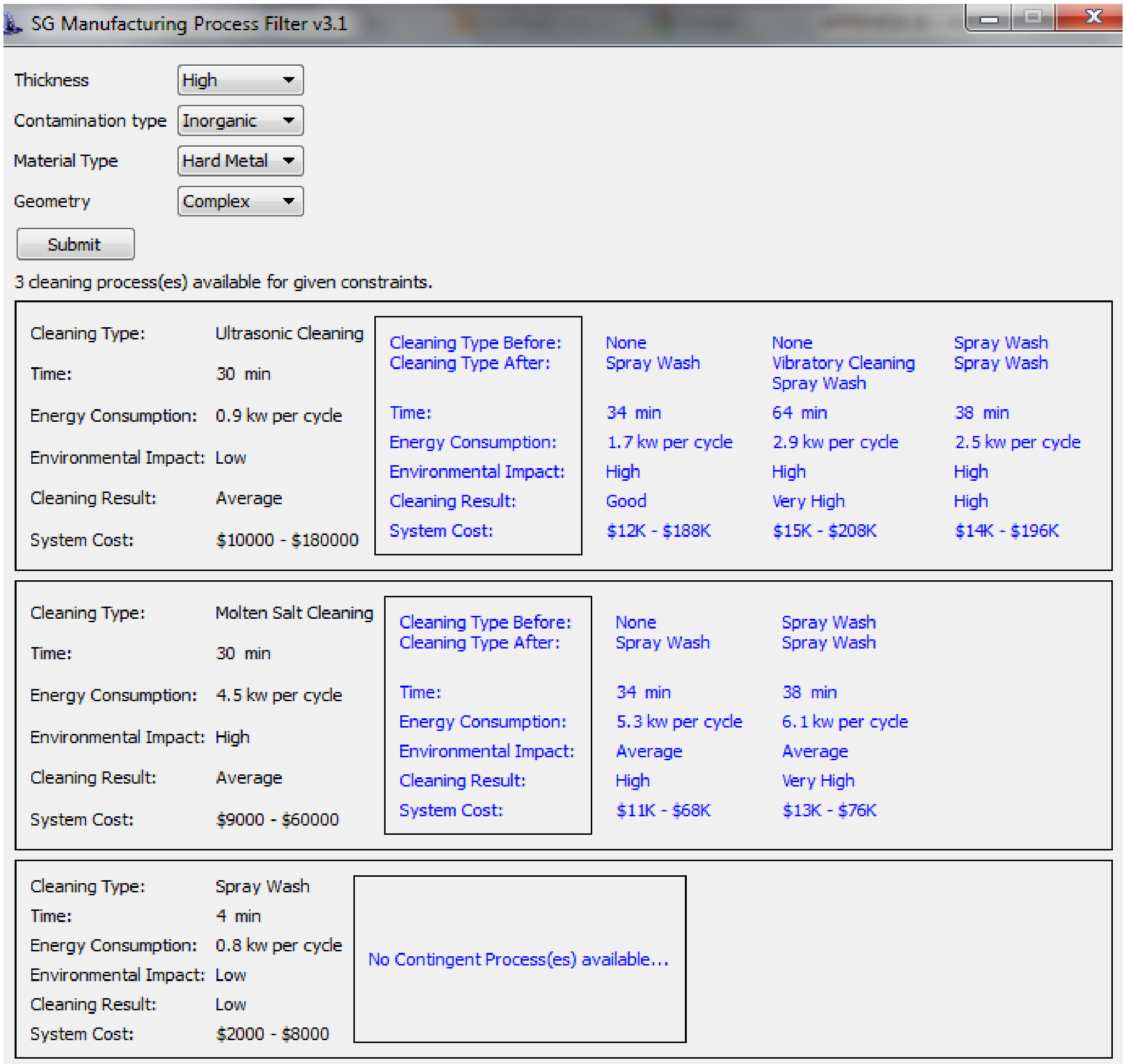
Result 44: High Organic Contamination Thickness, Other and Simple Part



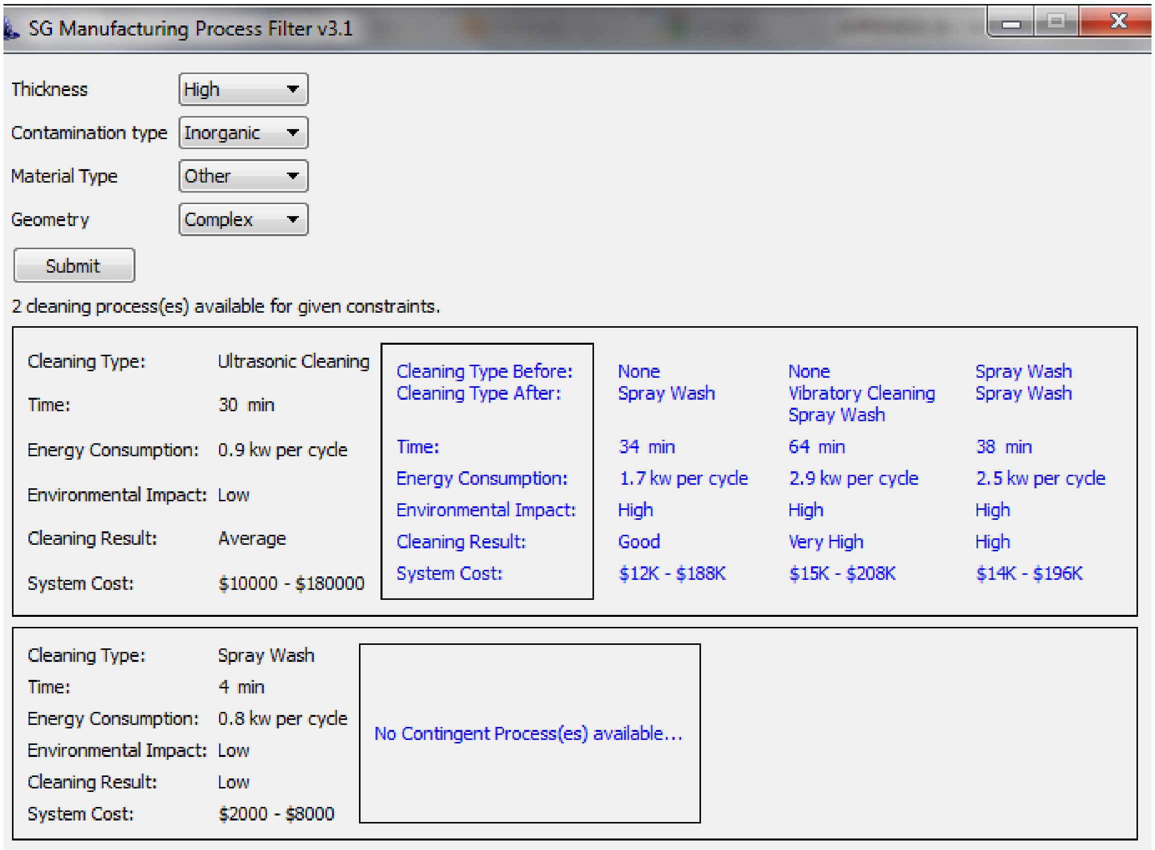
Result 45: High Inorganic Contamination Thickness, Soft Metal and Complex Part



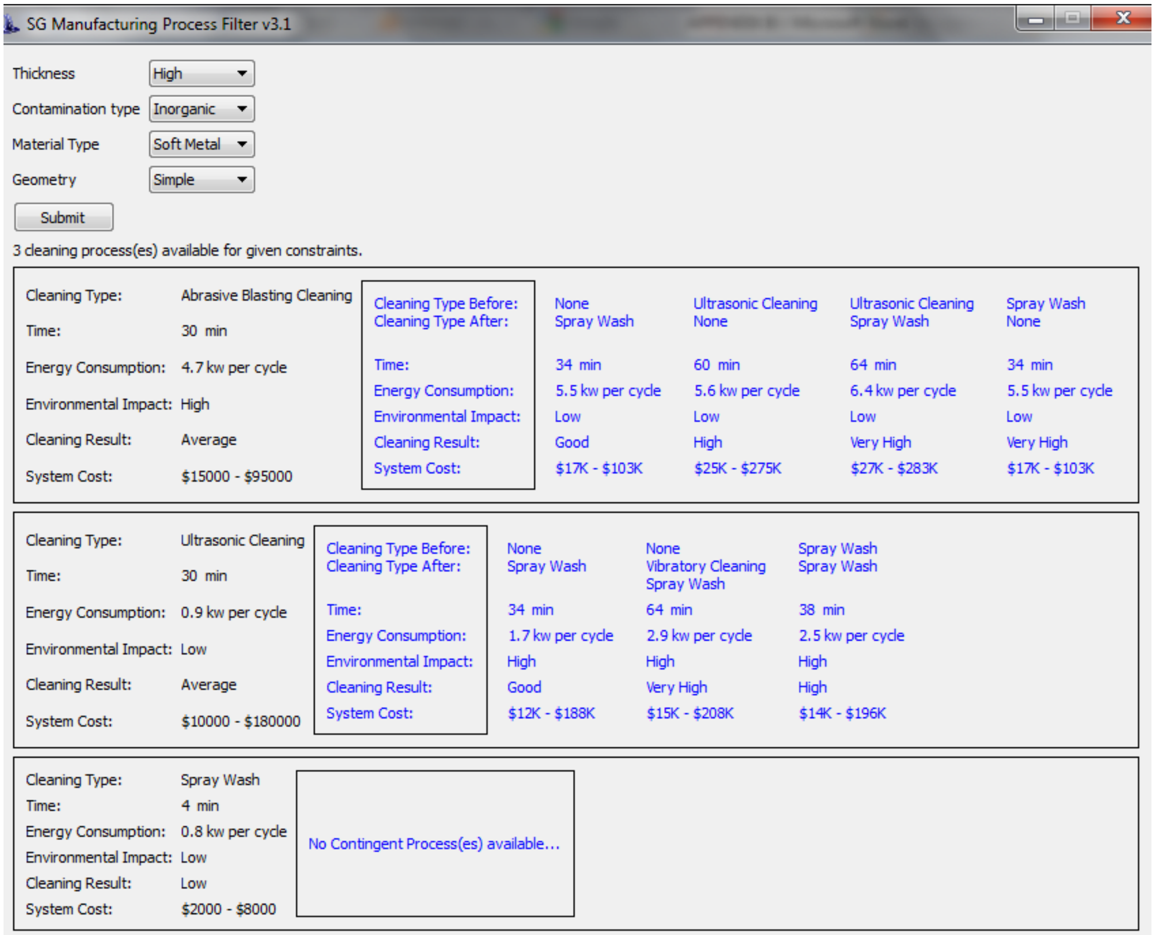
Result 46: High Inorganic Contamination Thickness, Hard Metal and Complex Part



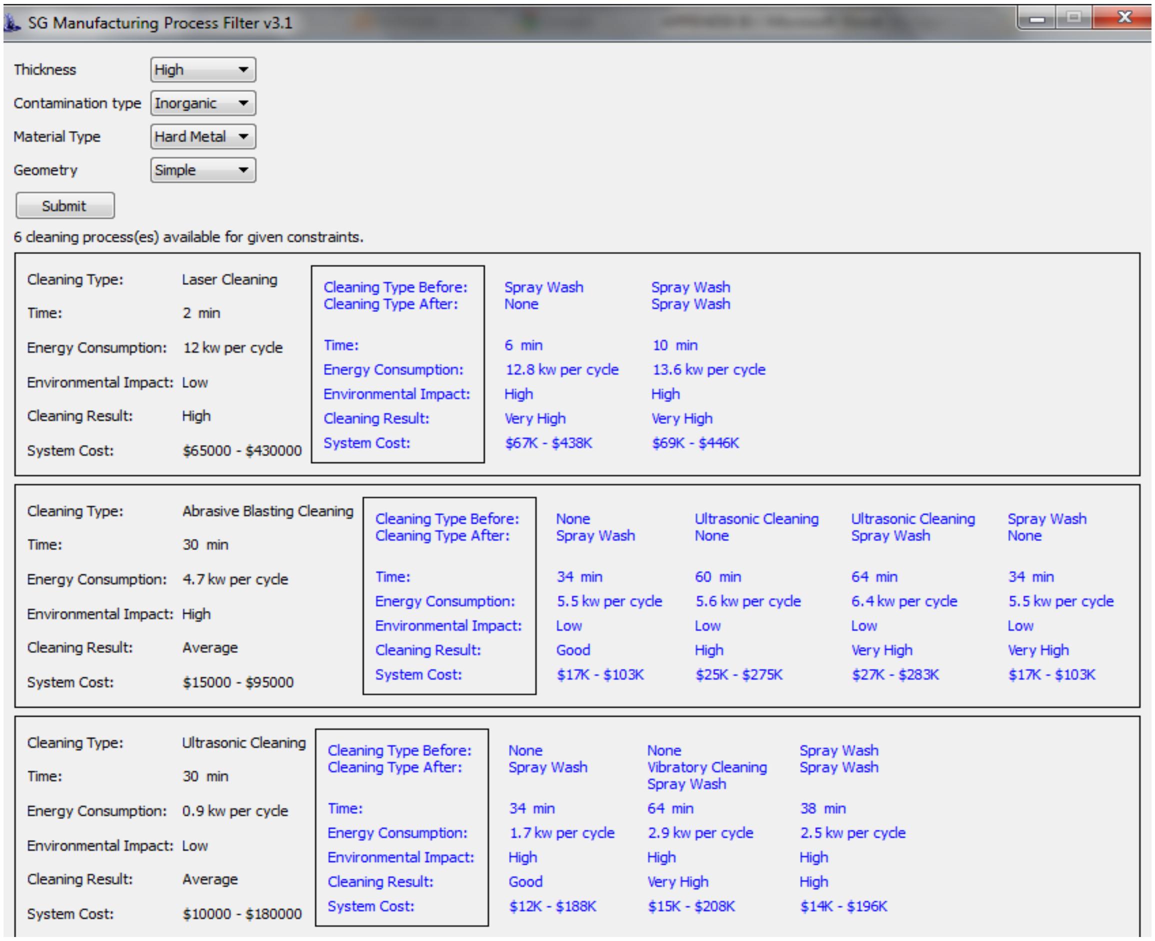
Result 47: High Inorganic Contamination Thickness, Other and Complex Part



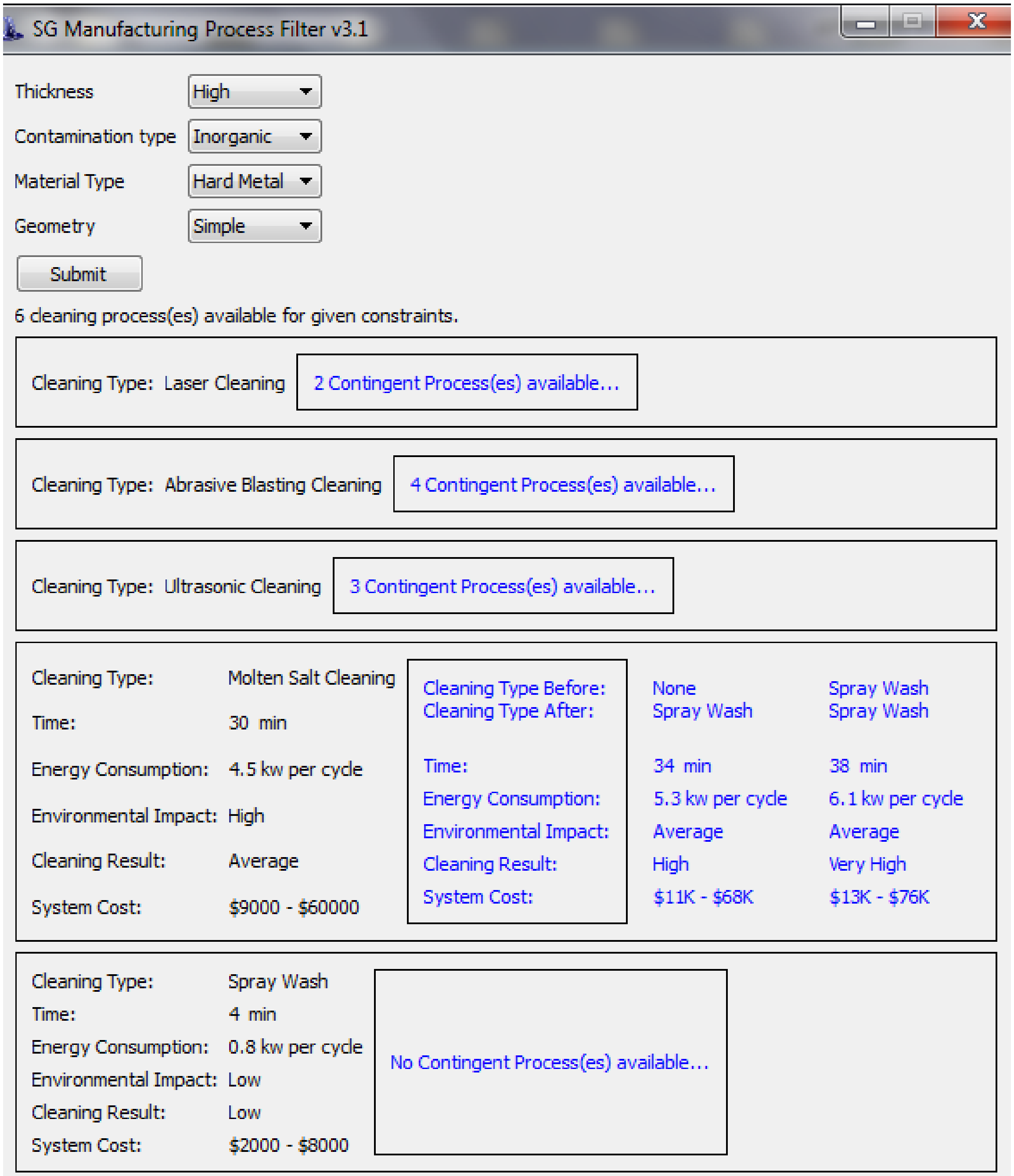
Result 48: High Inorganic Contamination Thickness, Soft Metal and Simple Part



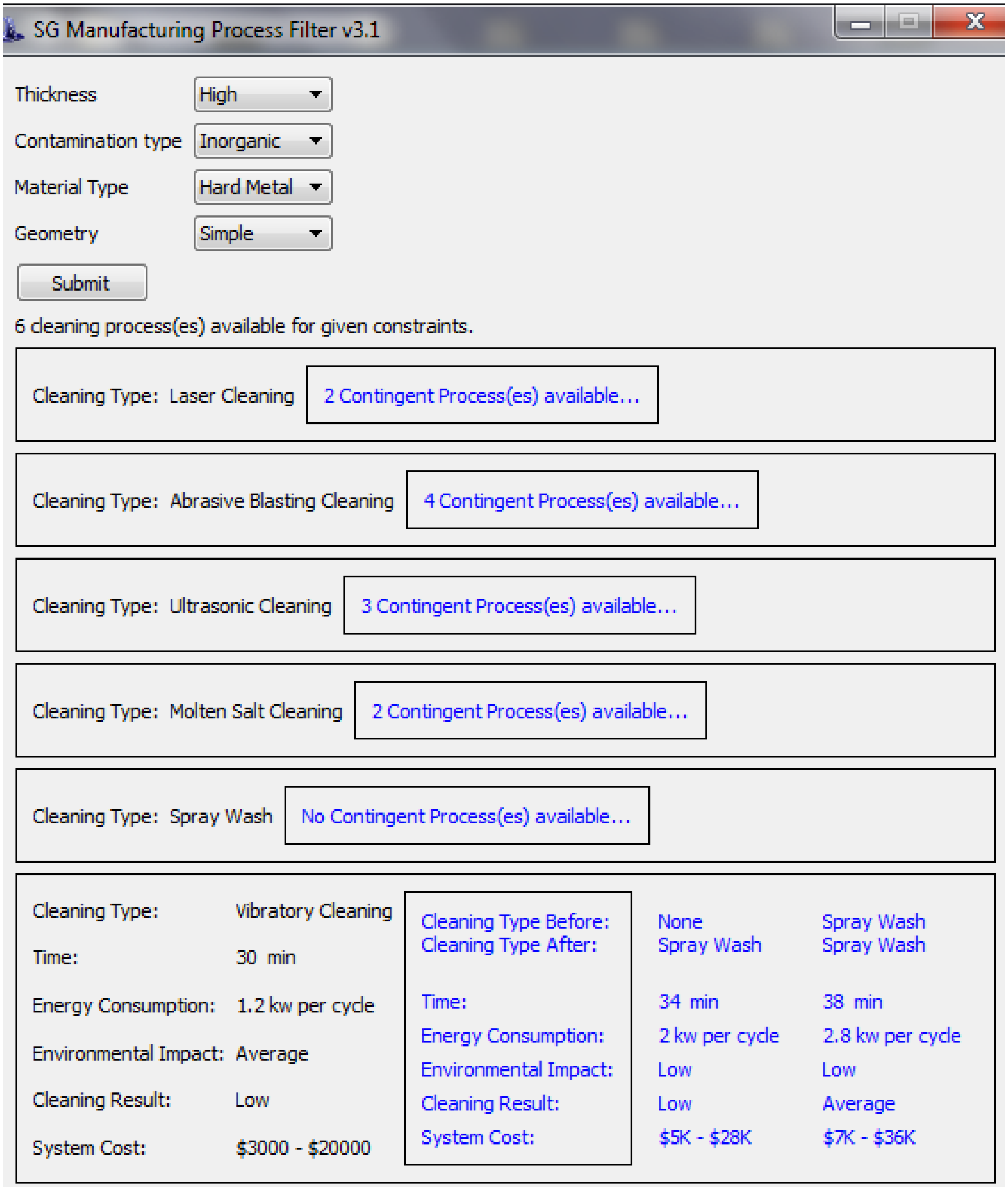
Result 49: High Inorganic Contamination Thickness, Hard Metal and Simple Part



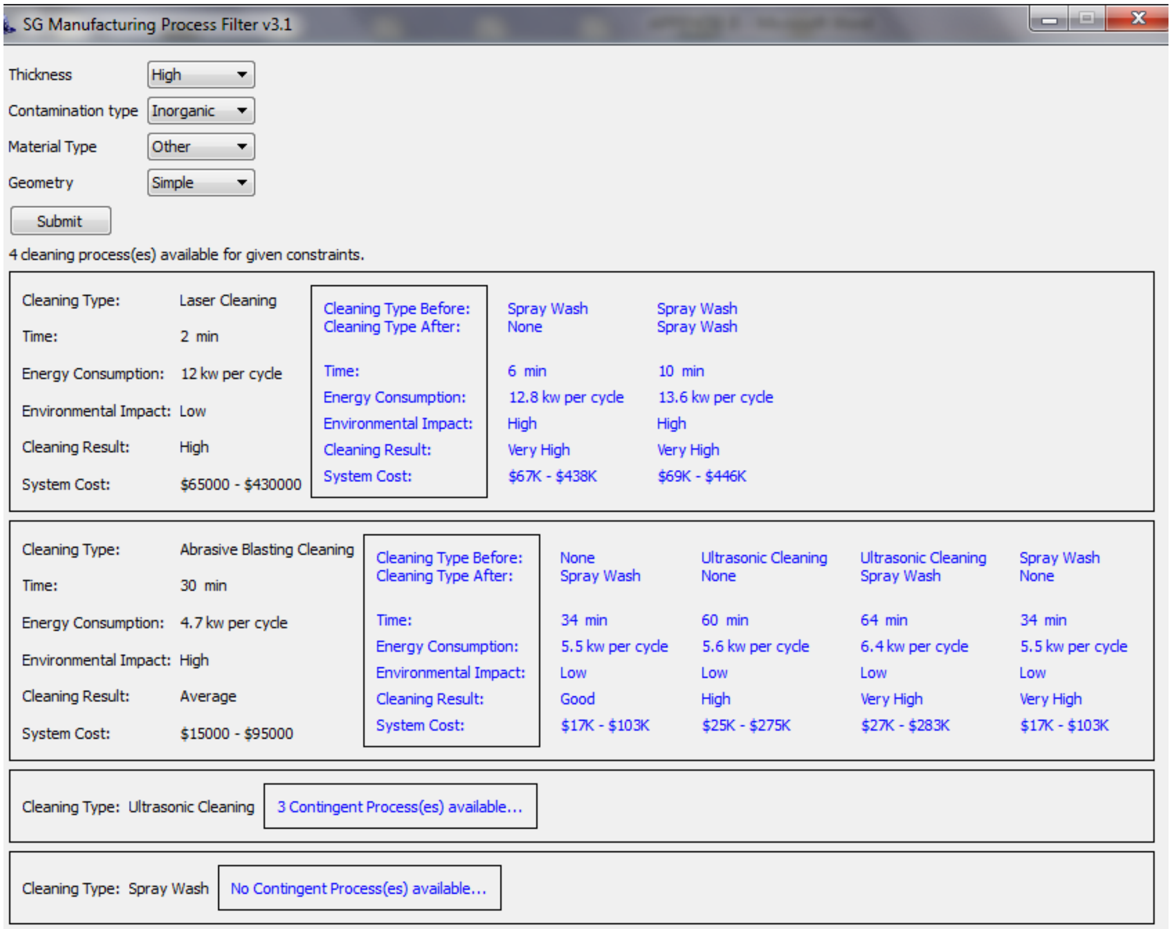
Result 50: High Inorganic Contamination Thickness, Hard Metal and Simple Part



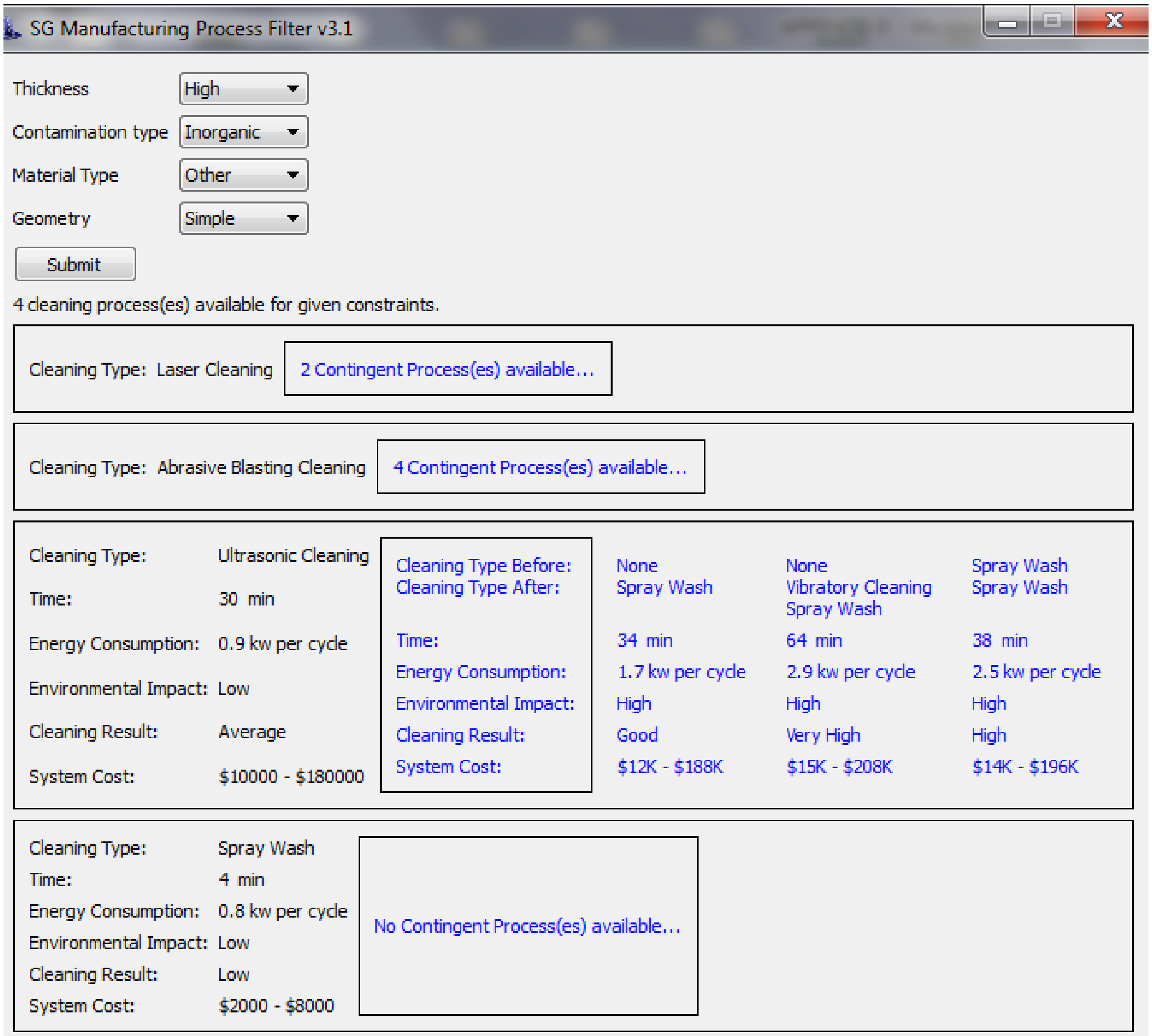
Result 51: High Inorganic Contamination Thickness, Hard Metal and Simple Part



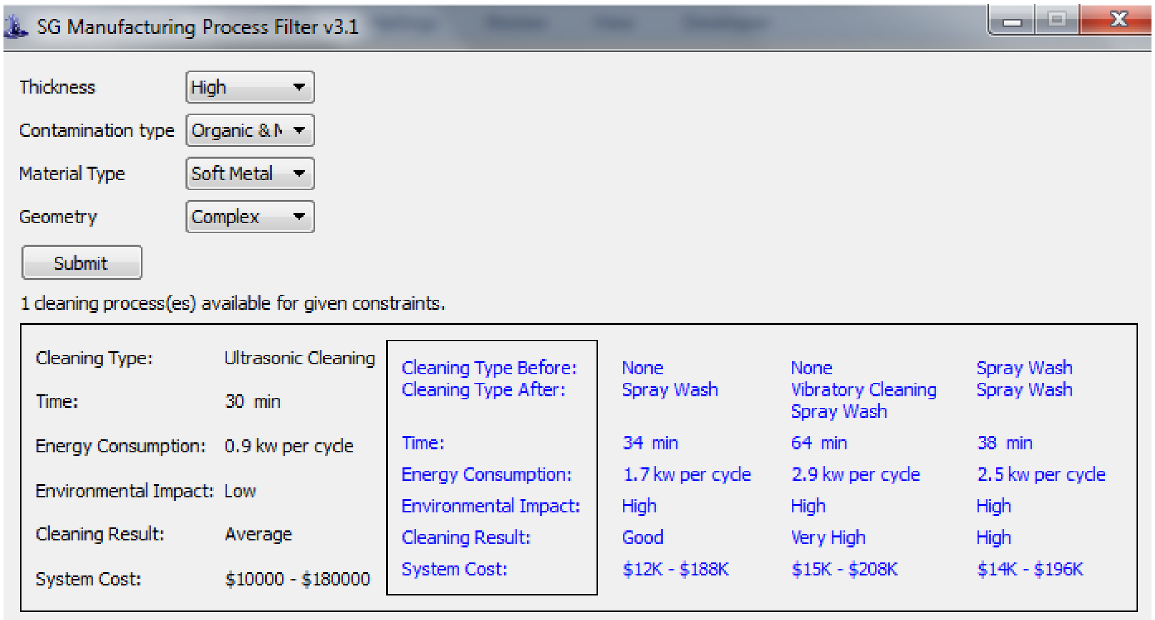
Result 52: High Inorganic Contamination Thickness, Other and Simple Part



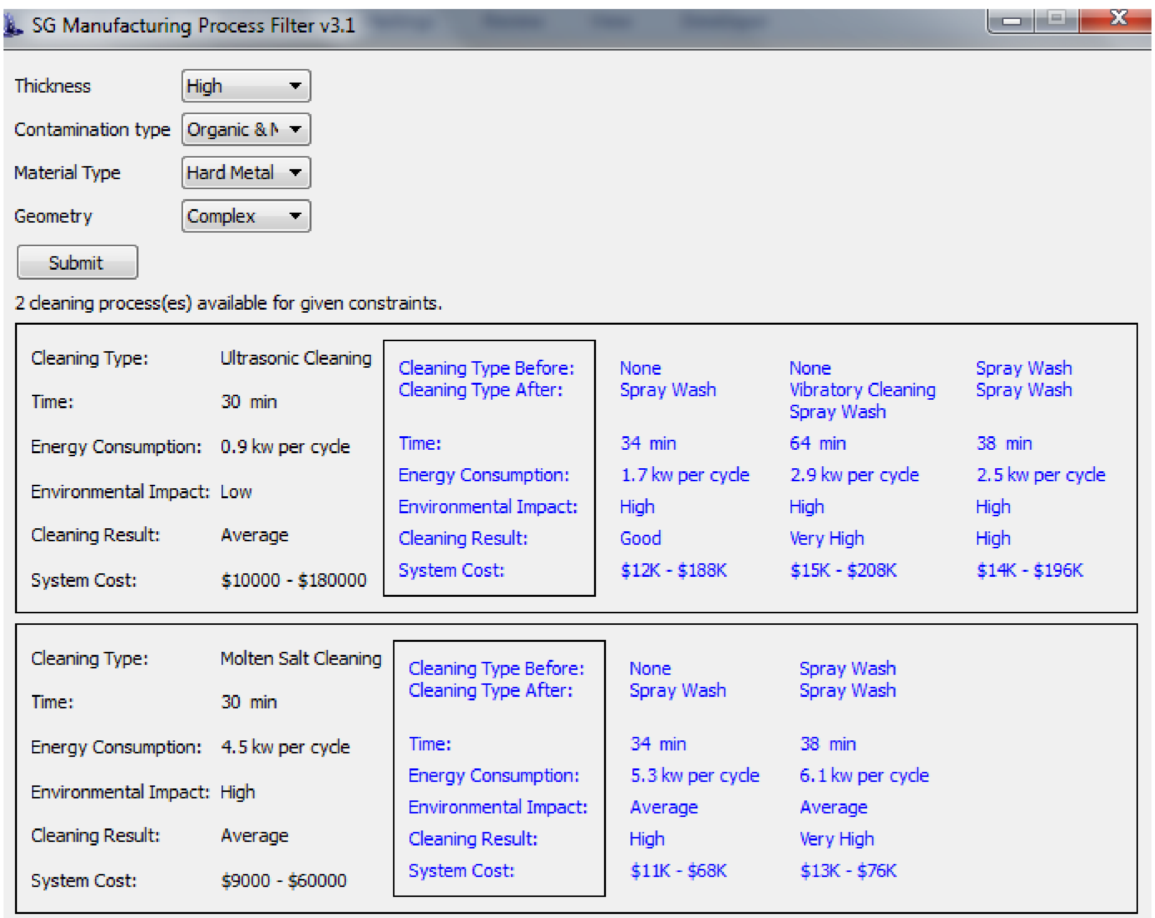
Result 53: High Inorganic Contamination Thickness, Other and Simple Part



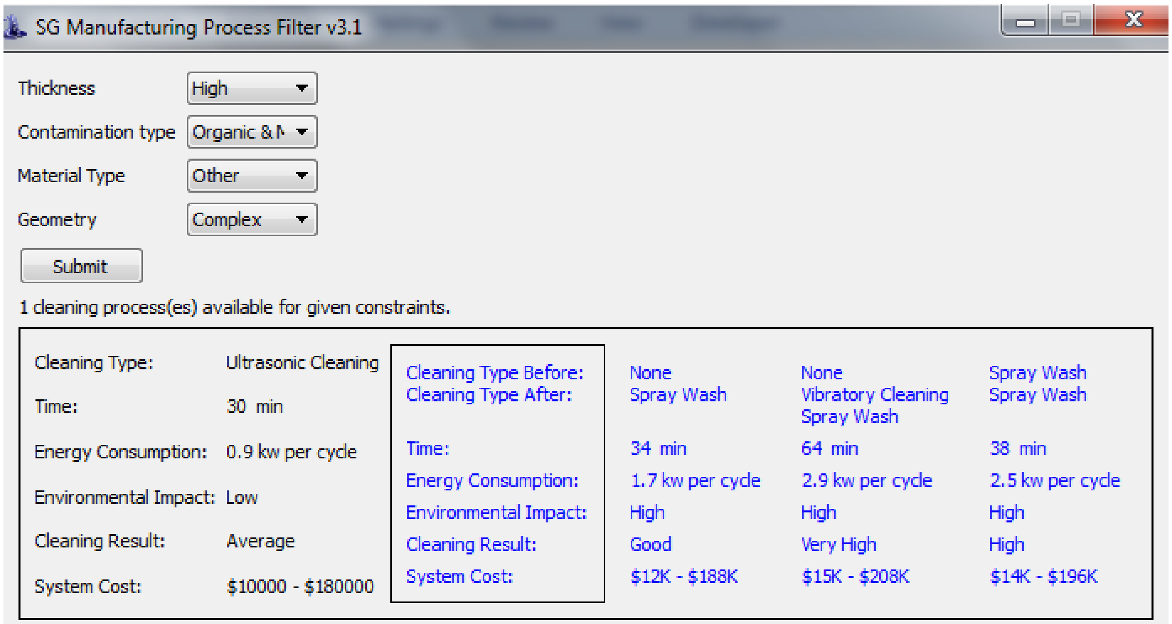
Result 54: High Organic & Mix Contamination Thickness, Soft Metal and Complex Part



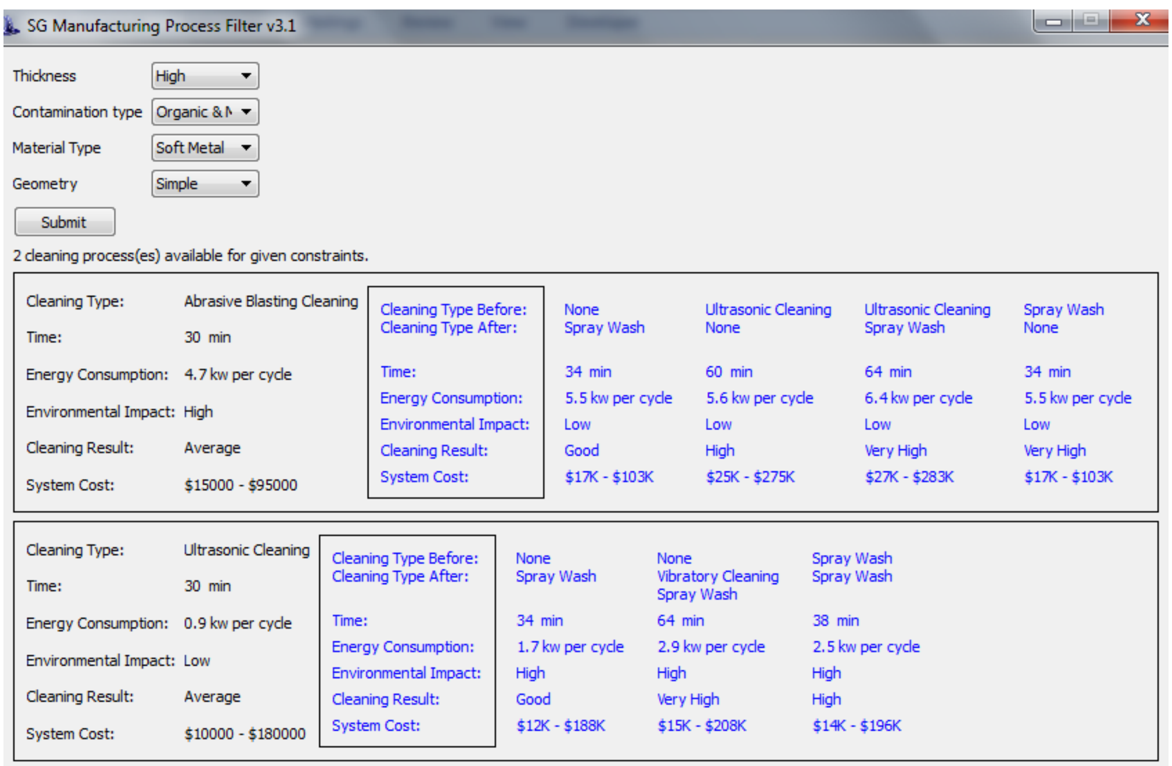
Result 55: High Organic & Mix Contamination Thickness, Hard Metal and Complex Part



Result 56: High Organic & Mix Contamination Thickness, Other and Complex Part

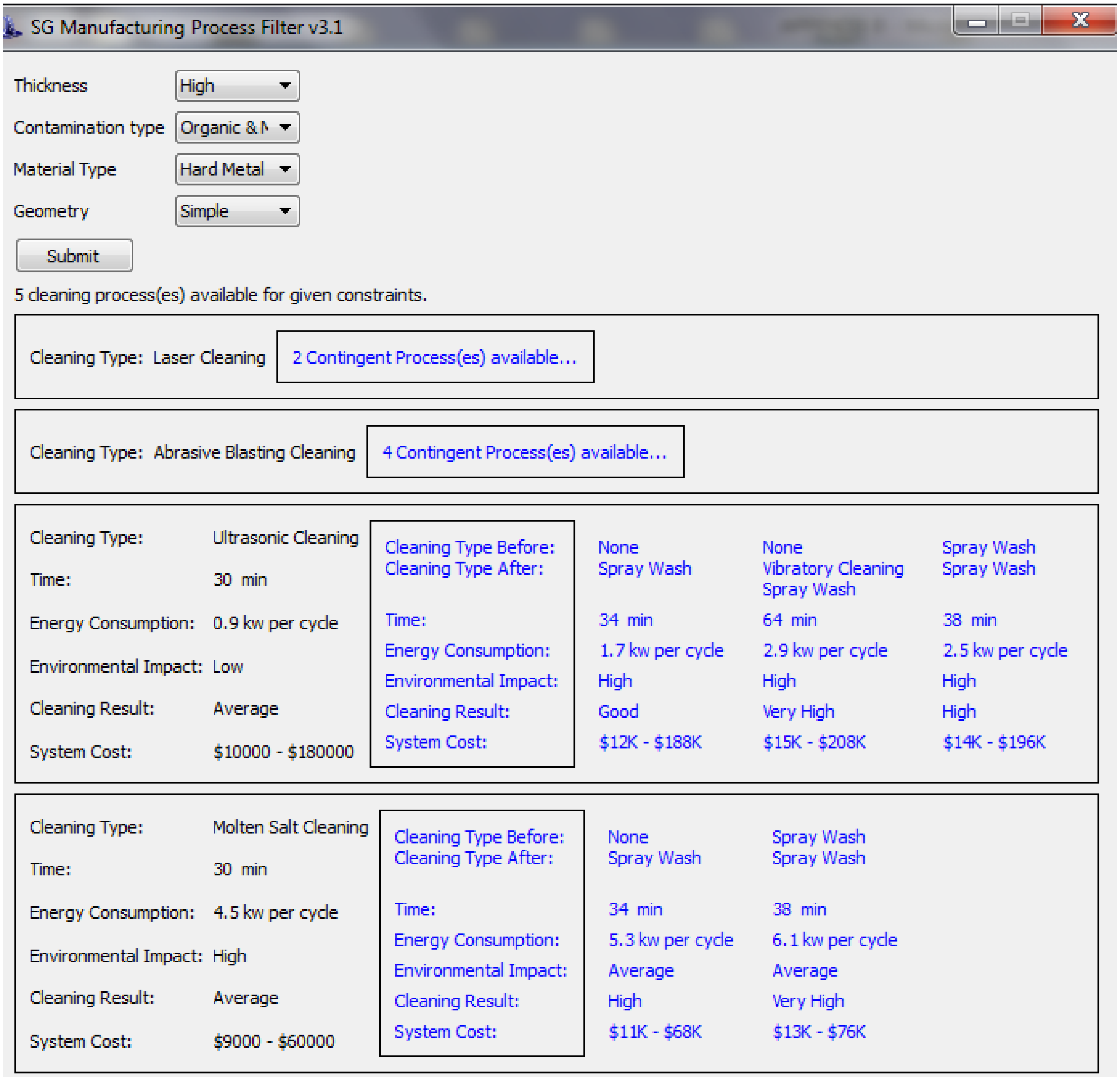


Result 57: High Organic, Mix & Inorganic Contamination Thickness, Soft Metal and Simple Part

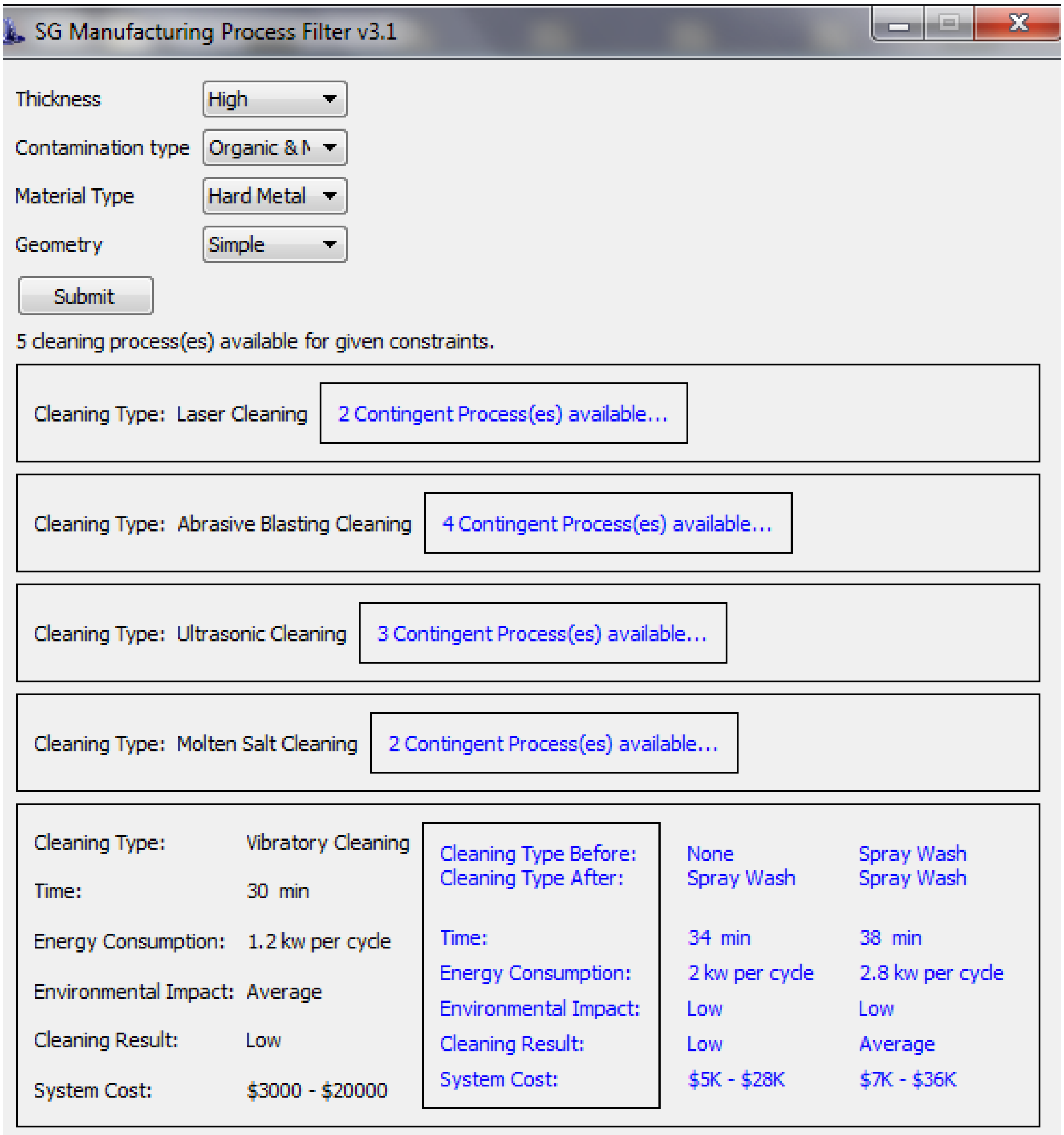


Result 58: High Organic, Mix & Inorganic Contamination Thickness, Hard Metal and Simple Part

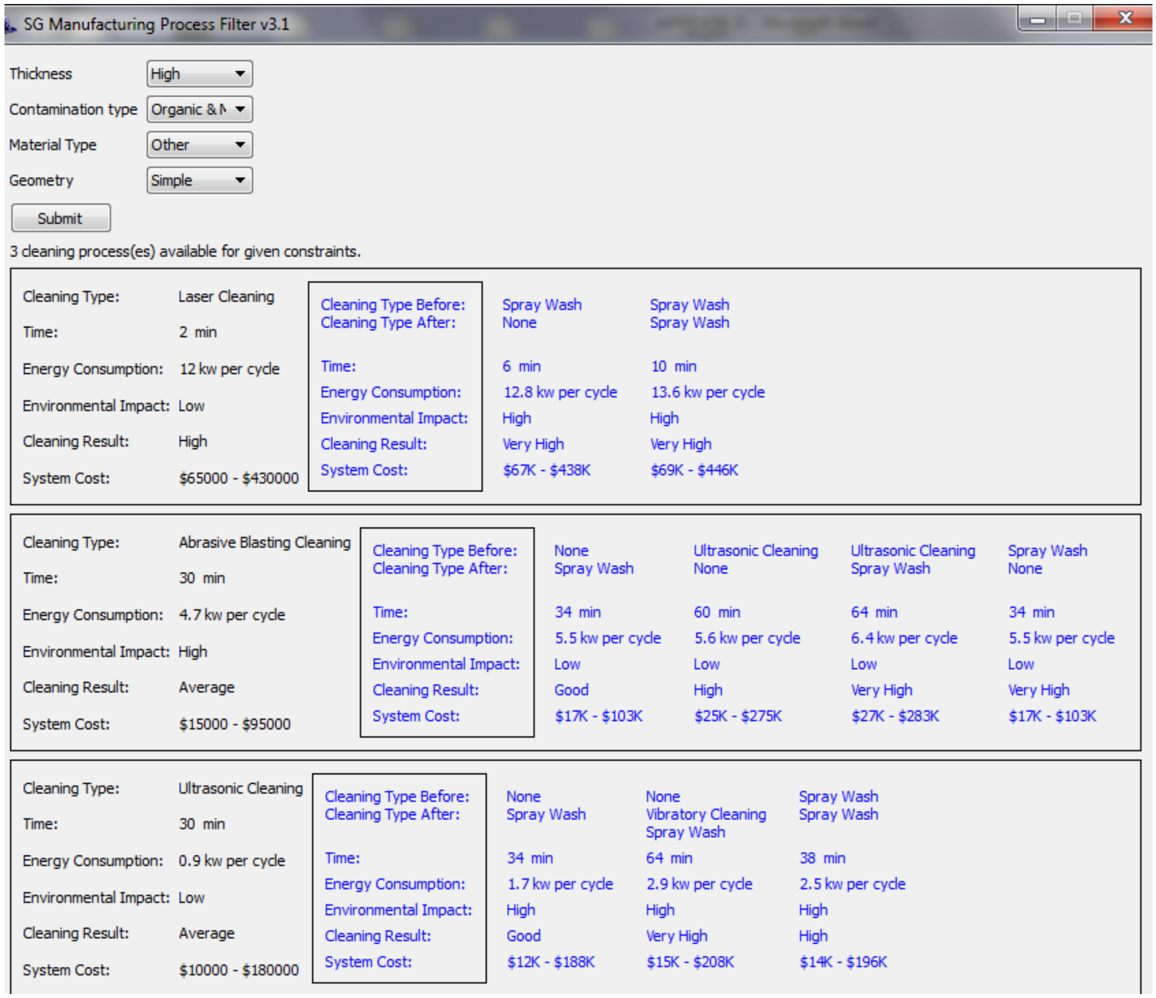
Result 59: High Organic, Mix & Inorganic Contamination Thickness, Hard Metal and Simple Part



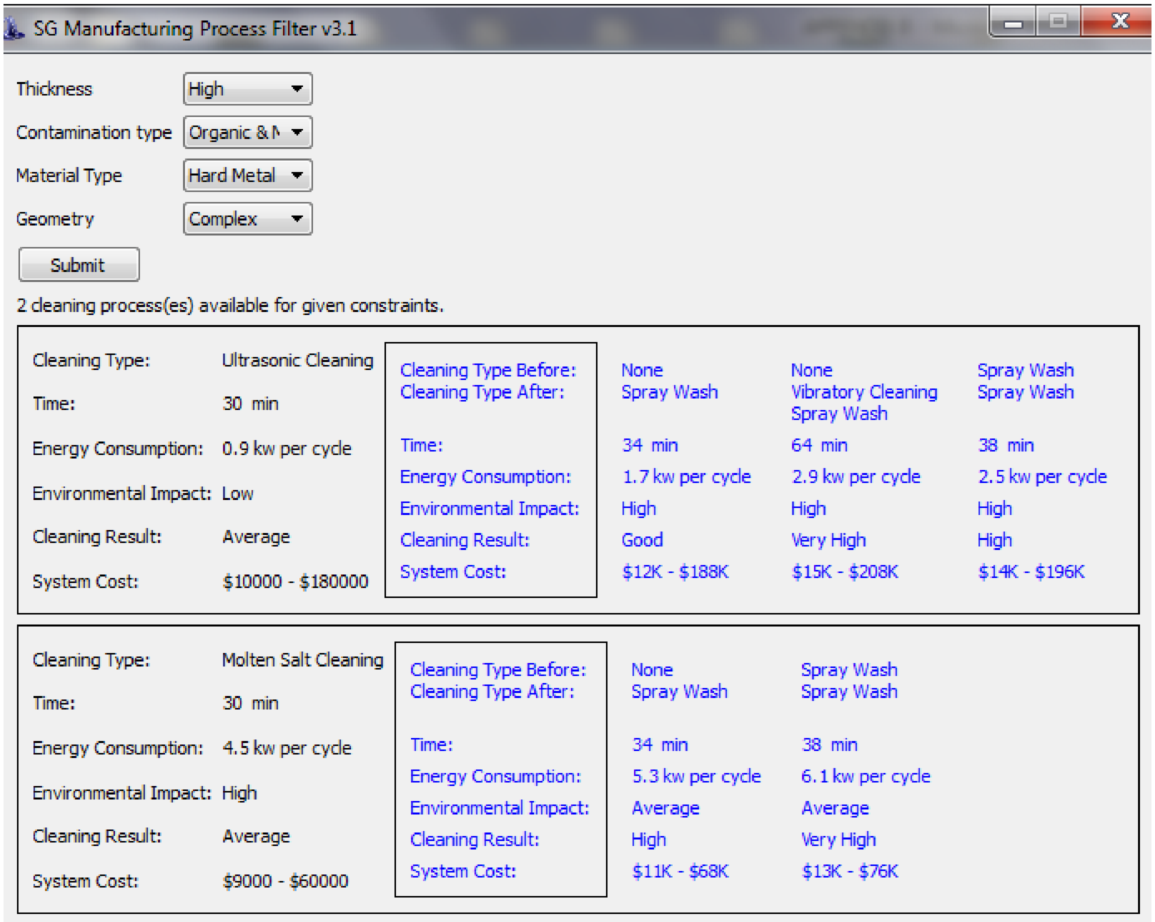
Result 60: High Organic, Mix & Inorganic Contamination Thickness, Hard Metal and Simple Part



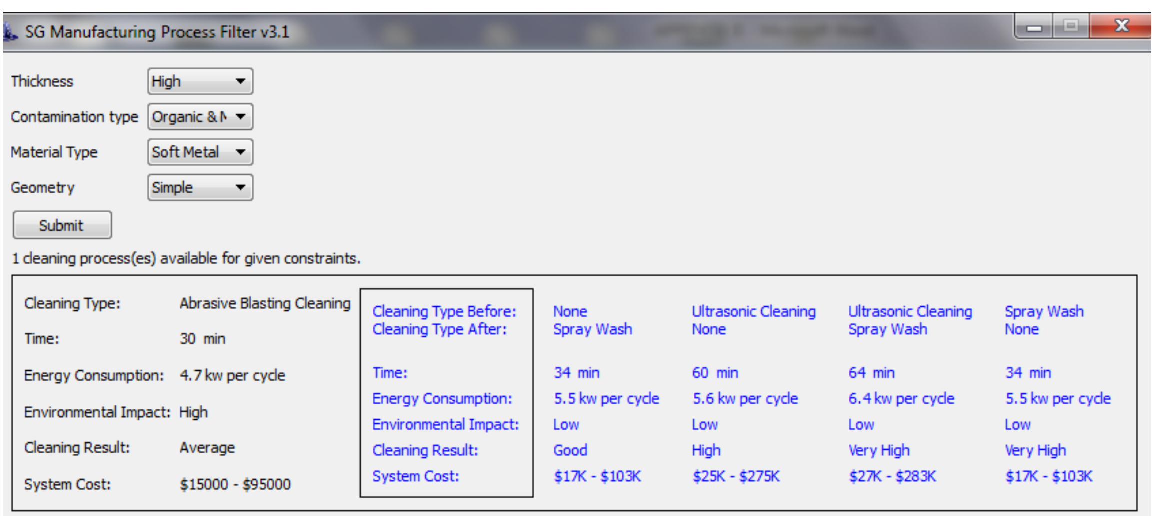
Result 61: High Organic, Mix & Inorganic Contamination Thickness, Other and Simple Part



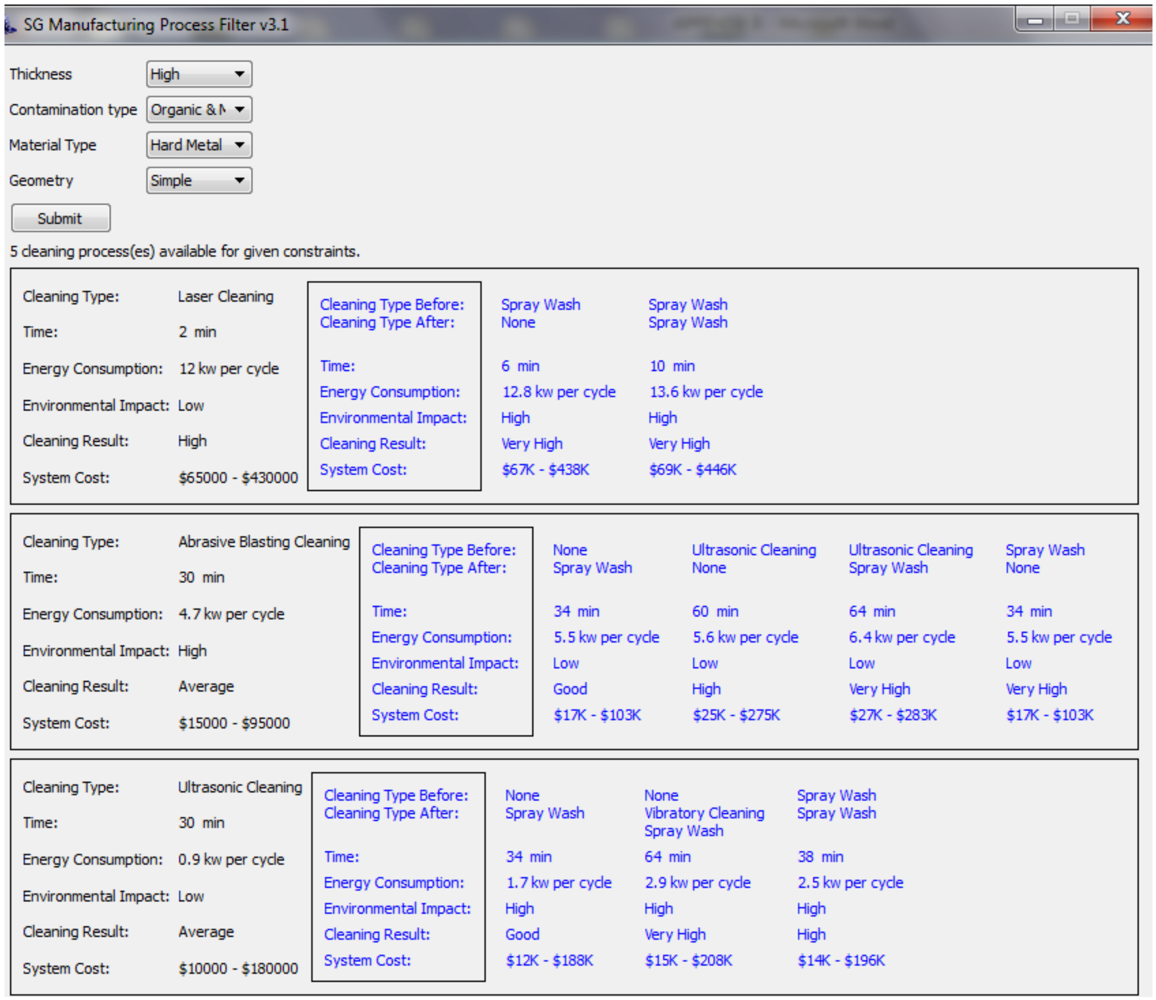
Result 62: High Organic, Mix & Inorganic Contamination Thickness, Hard Metal and Complex Part



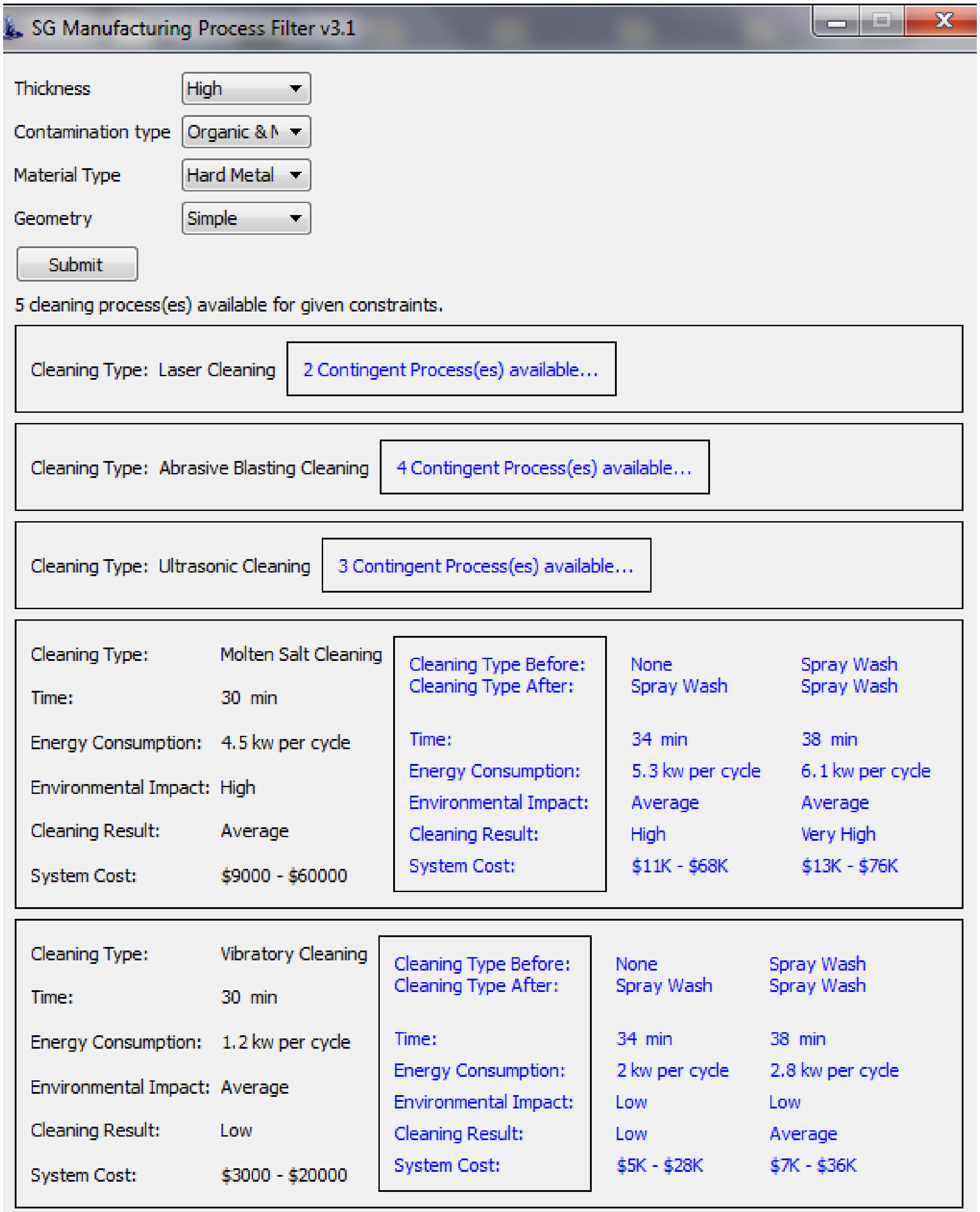
Result 63: High Organic, Mix & Inorganic Contamination Thickness, Soft Metal and Simple Part



Result 64: High Organic, Mix & Inorganic Contamination Thickness, Hard Metal and Simple Part



Result 65: High Organic, Mix & Inorganic Contamination Thickness, Hard Metal and Simple Part



Result 66: High Organic, Mix & Inorganic Contamination Thickness, Other and Simple Part

BIOGRAPHICAL SKETCH

Ozan Yagar was born in Mersin, Turkey in May 1987. His father is Orhan Yagar and mother is Nezihat Yagar. He entered Cukurova University in Adana, Turkey in 2005 and received his Bachelor's Degree in Environmental Engineering in 2009. In 2010, he came to the United States to pursue a Master's Degree in Manufacturing Engineering with a concentration in Engineering Management at the University of Texas Pan American. His research interests are in remanufacturing, rapid response manufacturing, system design and development, materials properties and processing, and nanotechnology. The author can be reached at ozanyagar@hotmail.com.