Construction of a Classification Hierarchy for Process Underspecification to Streamline Life-Cycle Assessment

by

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SUBMITTED TO THE DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN MATERIALS SCIENCE AND ENGINEERING

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MAY 2014

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ABSTRACT

Concerns over global warming potential and environmental degradation have created a demand for accurate assessment of the impact of various products and processes. Life cycle assessment (LCA), a quantitative assessment method, has been employed primarily to products, analyzing the energy inputs and environmental consequences for the manufacture and use of specific goods. While it has not seen widespread use in assessment of industrial processes, its methodology can be adapted for such purposes; indeed, LCA may be a powerful tool for analyzing processes. This thesis aims to explore the viability of LCA as applied to the process industry. Building on previous research designed to provide high-quality assessment despite varying levels of uncertainty associated with material inputs, this research constructs a system which classifies processes into a hierarchy based on their degree of underspecification. Simulations are performed using Oracle's Crystal Ball software to assess the usefulness and accuracy of the classification system. The system and its components are modified and tested again to achieve better results. Owing to time constraints and fundamental differences between energy inputs for processing different types of materials, the classification system presented herein concerns itself only with metals. Nonetheless, this system seeks to provide a logical approach to process underspecification, and lays the foundation for similar systems for other processes and other types of materials.

Thesis Supervisor: Elsa Olivetti

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Acknowledgments

I am quite grateful for the opportunity to get involved in this work. I would like to extend my sincere gratitude to my thesis advisor Elsa Olivetti, without whom none of this work would have been possible. She has been an excellent mentor, and was very helpful in guiding me through research, testing, writing, and editing. I would also like to thank Jocelyn and Stian for suggesting literature and helping me with hierarchy construction.

Huge thanks are due to my good friend Matthew Brenner, who hosted me at his place in Philadelphia over Patriot's Day weekend, when I wrote a significant chunk of this document. Great documents get written in Philadelphia, after all.

Finally, I would like to thank my parents for all their support and encouragement that brought me to this point. You are great.

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1. Introduction

The purpose of life cycle assessment (LCA) is to quantify the environmental impact of a product or process over its life cycle (Jacquemin, Pontalier, & Sablyarolles, 2012). It is no surprise, then, that LCA has become increasingly relevant in the modern world. Fluctuations in energy prices makes it desirable to investigate how to reduce energy inputs; the recent trend of 'going green' to reduce environmental degradation requires accurate assessments of industrial emissions. Thus, methodologies which can reasonably generate this information, such as LCA, are in demand. Indeed, the popularity of LCA has grown enormously since its founding, going from about a dozen studies in the early 1970s to being the subject of an international initiative by the United Nations Environment Programme in the 2000s (Curran, 2006).

Of course, any such assessment must address the question of what the life cycle of a process or product is; this depends on the nature of the assessment. Fundamentally, a manufacturing process can be described in terms of thermodynamic parameters, accounting for mass, heat, and work flows within and across specific boundaries (Gutowski, Branham, et al. 2009). An important component of analysis, therefore, is choosing boundaries relevant to the problem at hand – whether it's the operation of a single piece of equipment in a factory, or a complex series of operations. Boundaries may be 'cradle to gate,' in which the analysis concerns itself with impacts arising from extraction of raw materials until the end of processing, 'gate to gate,' in which case the boundaries encompass only certain industrial operations, or 'cradle to grave,' which is like cradle to gate but also extends to the impacts from a product's use and end of life. In the case of products and services where energy is not consumed in the use phase, the distinction makes little difference, as the most energy and emissions intensive processes take place before reaching the consumer; cradle to grave analysis is more significant for electric and electronic products, and also if recycling is to be considered or disposal of hazardous waste is required. Methodology may have to be tweaked to account for byproducts which occur for or last for hundreds of years, such as radioactive waste (Frischknecht, 2007). For purposes of this paper, analysis will be gate to gate, with the boundary defined as the machinery used to perform the processes analyzed.

Once the boundaries for the LCA analysis have been established, one must prepare an inventory assessment, and acquire data to do the impact assessment for the inventory. While there are numerous databases cataloguing hundreds of thousands of inputs and emissions for various processes and products, special care must be taken to ensure that the data obtained are used appropriately. This will be discussed in further detail in the methodology section. It is also important to note that fully accurate life cycle assessment is not practical, owing to the tremendous amount of detail that would be necessary in gathering all data. Even if such accurate data were collected, it would not be perfectly applicable to operations under different conditions. Thus, it becomes necessary and practical to use data in a more general way. This work focuses on probabilistic underspecification, a method to streamline life cycle assessment by accounting for uncertainty in data.

1.1 Uncertainty and Probabilistic Underspecification

In order to be useful, life cycle assessment must strike a balance between accuracy and convenience: on one hand, an assessment must convey accurate information about what it purports to assess, and be relatable to similar situations. The assessment must also be done in a relatively transparent manner, ensuring that it can be repeated and verified. On the other hand, it must also be done in a convenient and efficient way: as mentioned previously, meticulously cataloguing all inputs and emissions at every stage of life for a product might be accurate and repeatable for that very specific case, but it would also be prohibitively costly if used generally. Such precise information might not even be possible to obtain – owing to the globalized economy of the modern era, inputs may come from all around the world, often from third parties which might not be willing to disclose necessary details. Considering that some products and processes involve hundreds or even thousands of inputs, it becomes nearly impossible to obtain highly accurate data. Some degree of uncertainty in LCA data must not only be tolerated, but may be necessary.

One way of dealing with lack of data is to employ a first principles approach, estimating the energy of a process from the actual physical energy change – for example, using the specific cutting energies of aluminum alloys to estimate the energy in an aluminum alloy cutting operation (Dahmus & Gutowski, 2004). This type of estimate may be useful, but does not hold up in cases where the energy of the machines used in the operation is significantly greater than simply the physical energy of the process. As Figure 1 demonstrates, depending on the machine used, the actual energy of the process may or may not constitute the majority of the energy of the operation being examined. Consequently, using first principles estimates in the face of uncertainty about the actual operation is not likely to yield particularly useful or meaningful results.

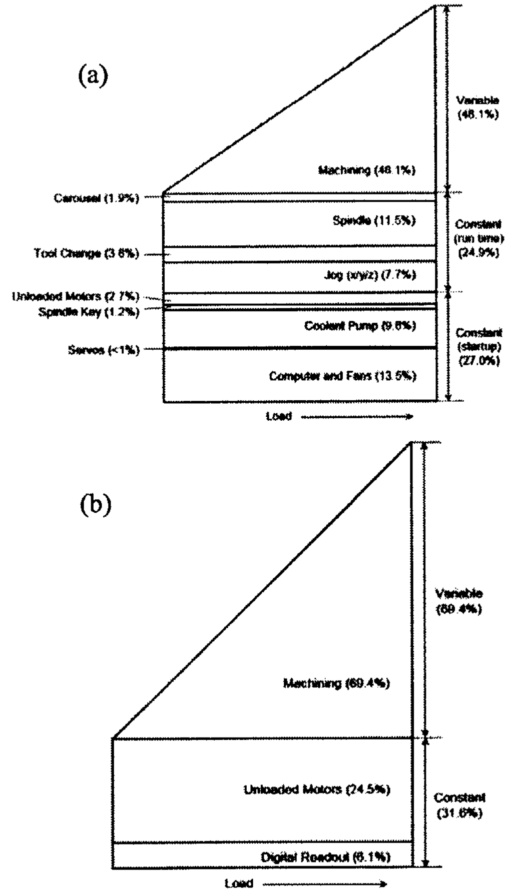


Figure 1 (a). Energy breakdown for a 1988 Cincinnati Milacron milling machine. (b). Energy breakdown for a 1985 Bridgeport milling machine. Adapted from Dahmus & Gutowski, 2004.

Another method for dealing with a lack of primary data in LCA is modifying scope – for a certain assessment, one can identify a "set of interest," or SOI (Patanavanich, 2011). Even if an exact contribution towards the product or process as a whole is not known, if one knows that this particular contribution is small compared to other major contributions, then it might be appropriate to approximate it using generalized information. Other modifications to scope may improve life cycle assessment: while it may be ideal to have all the information for the inputs and emissions of products or processes, such an analysis may not be practical, and there may yet be utility in focusing on the contribution of a smaller subset. For instance, it may be desirable to have data throughout an entire industry to figure out what the industry as a whole could do to reduce greenhouse gas emissions; however, if industry-wide collaboration is not possible, individual firms within the industry might nonetheless find it useful to conduct their own, smaller-scale assessments (Todd & Curran, 1999). If process inputs and emissions vary widely depending on whether operations are large or small scale, altering the scope may indeed improve LCA results.

Ultimately, life cycle assessment is a quantitative technique, and it would be helpful to establish definite bounds for the uncertainties resulting therefrom, rather than simply using good judgment in selecting which parameters to use or approximate. It was from this need that the concept of structured underspecification emerged. Patanavanich and collaborators designed this method, developing a hierarchical classification system that classifies materials into discrete hierarchies depending on the level of specificity (Figure 2)

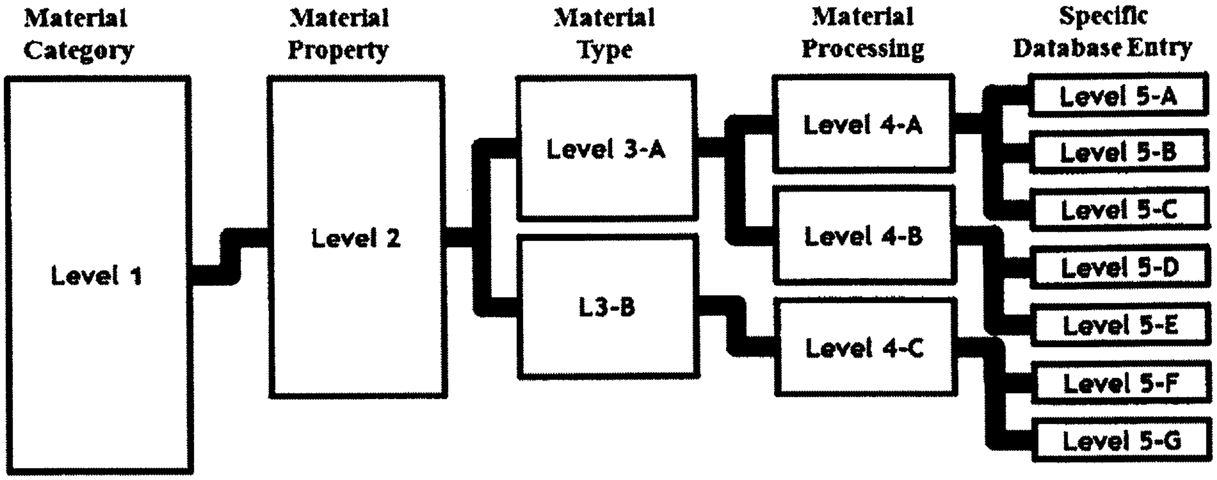


Figure 2 Hierarchical classification of structured underspecification system. Each level has a higher level of specificity than the one to its left. Adapted from Patanavanich, 2011.

It was found that a well-constructed hierarchy system showed lower values of the Median Absolute Deviation Coefficient of Variation (MAD-COV) for emissions estimates as the level of specificity increased (Patanavanich, 2011). Moreover, it has been demonstrated that lower-fidelity data points can supplement higher-fidelity data points in a so-called 'probabilistic triage' to improve life cycle assessment. As Olivetti reports, by using a combination of high-fidelity and low-fidelity data for the given SOI, the MAD-COV for the final product is comparable to the MAD-COV achieved through only high-fidelity data, and much less than the MAD-COV obtained through only low-fidelity data (Olivetti, Patanavanich, & Kirchain, 2014). Thus, the probabilistic triage succeeds in quantifying useful information for life cycle assessment at reduced cost. This way of streamlining life cycle assessment enables a practitioner to obtain less specific information about the type of activities associated with the object of the study, yet still obtain an effective assessment.

1.2 Application of Life Cycle Assessment to Processes

So far, life cycle assessment research has largely focused on inputs and emissions for specific materials and products. This is not particularly surprising given the interests of many firms conducting life cycle assessment: if a company conducts LCA with the aim of making their products more 'eco-friendly', the focus would naturally be on the material inputs and emissions for the product; collecting data to generalize the impact of the processes involved in the product's manufacture may be deemed less important, especially if the processes are upstream and beyond the scope of the assessment. However, gathering data from a product-oriented perspective has its limitations, especially in industries where manufacturing techniques are frequently updated. One such example is the semiconductor industry, which evolves so rapidly that by the time a thorough life cycle assessment can be completed, manufacturing has likely already started on a newer model (Murphy, Kenig, et al. 2003). In that instance, generalized data for the process of wafer fabrication may be more useful.

By employing data gathered for individual processes, products can be assessed from a bottom-up perspective. Such a method has already been developed to improve life cycle assessment for semiconductor manufacturing: Murphy et al. model manufacturing as a series of parametric modules, analyzing wafer production by its constituent processes, such that they can generally make accurate estimates of the inputs and emissions for semiconductors (Murphy, Kenig, et al. 2003). However, the promise of this process-oriented view is not limited to just semiconductor manufacture and other rapidly-evolving industrial techniques. Indeed, it has the potential to impact all types of manufacturing. Ideally, if data on a sufficient number of processes were collected, any product could be broken down into its constituent processes, and the inputs and emissions for the end product could be determined from the sum of inputs and emissions for individual processes. This could apply to something as simple as the manufacture of a soda can, or something as complex as the manufacture of an incinerator (Figure 3).

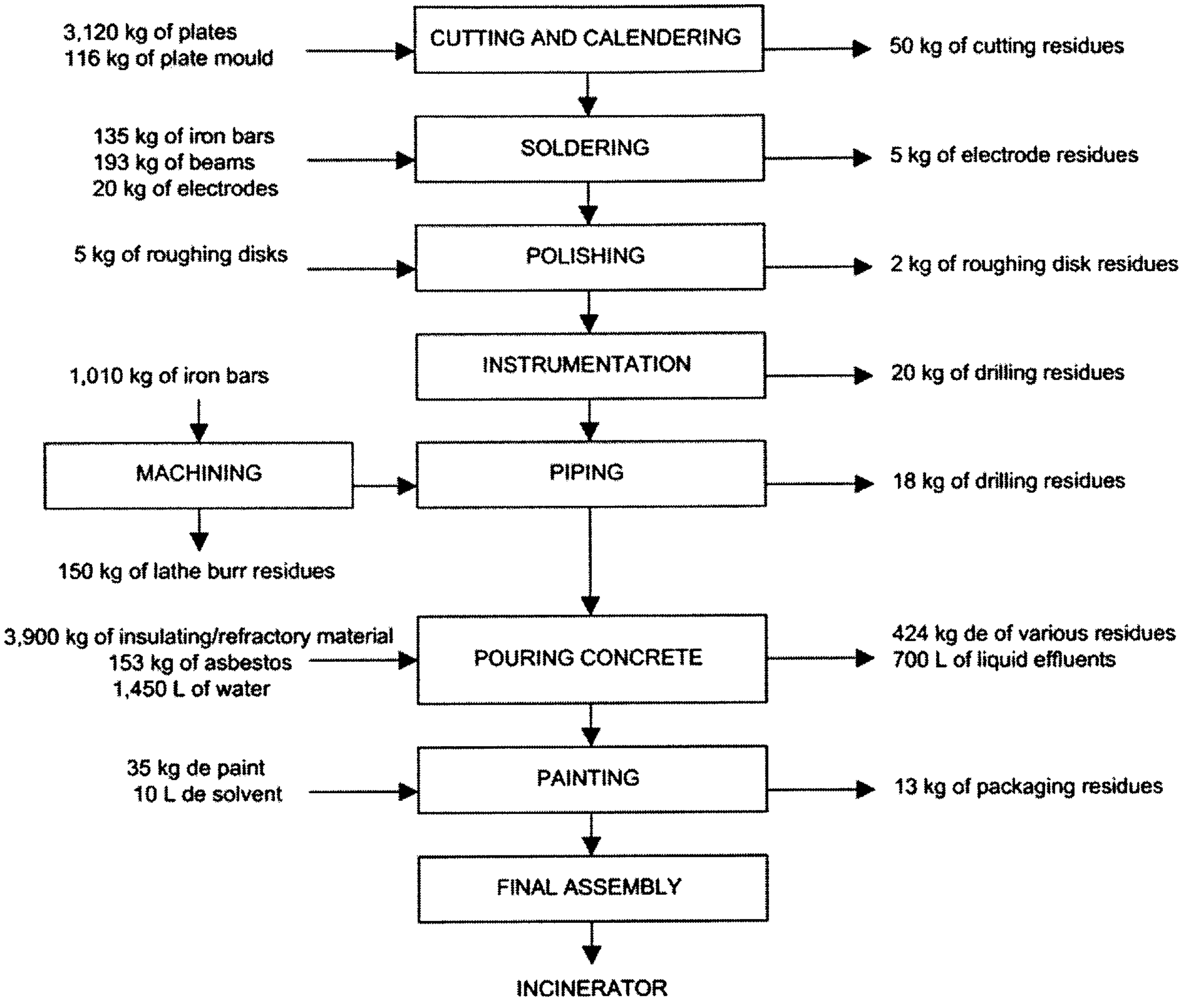


Figure 3 The manufacture of an incinerator is broken down into its component processes, each of which has its own input and emission data. Adapted from da Silva & Amaral, 2009.

If this type of process-based life cycle assessment were adapted for more general use, its consequences could be profound. “Design for the environment,” a paradigm by which producers would develop products and operations with environmental consequences in mind, could become much more widespread (Jacquemin, Pontalier, & Sablyarolles, 2012). Depending on the accuracy of LCA simulations, one could even conduct LCA before establishing operations, enabling producers to evaluate environmental impact from the very beginning of the manufacturing process.

1.3 Goals of This Research

While a complete framework suitable for widespread industry use is as of yet unrealizable, the components to begin construction of such a framework are there. This thesis aims to apply underspecification to manufacturing processes, which will enable low fidelity quantification of manufacturing processes where detailed information does not yet exist, thereby laying the groundwork for streamlining life cycle assessment. To determine what principles are important in the construction of a classification hierarchy system for manufacturing processes, various hypotheses will be put forth and tested. The test results will show the highlights and shortcomings of initial hypotheses, which may be modified or discarded in favor of new hypotheses. Many hypotheses involve specification of material type: as processes on the same type of metal might have similar energies, it is important to figure out at which level of the hierarchy it would be best to specify this. Finally, once smaller hypotheses for material classification have been adequately tested and refined, this research will present an attempt at a broad, overarching classification system which could theoretically be expanded to account for all materials processes which can be described in units of energy per kilogram of material processed. Regardless of how useful this particular hierarchy is for process-based life cycle assessment, it is one of the first attempts at such a comprehensive system, and as such provides much useful information for future research. Ultimately, this research aims to serve as a springboard for future process-based LCA research, which will hopefully become widespread and raise awareness of environmental issues associated with industrial processes.

2. Methodology

Employment of a structured underspecification system facilitates use of the probabilistic triage method, thereby streamlining life cycle assessment. This section describes the methods which went into developing a classification hierarchy for industrial operations on metals. The hierarchy consists of five levels, increasing in order of specificity from level L1, the most underspecified and least certain level to level L5, which consists of individual entries on specific industrial process energies.

2.1 Data Collection

Several data points were gathered for the construction of L5 points, drawing from sources such as the ecoinvent Life Cycle Inventory database (Frischknecht, 2007), the Department of Energy-Rutgers University Industrial Assessment Centers database (Industrial Assessment Centers Database), the U.S. Life-Cycle Inventory Database (LCA Digital Commons), as well as various papers on specific processes (Steiner & Frischknecht, 2007) (Dahmus & Gutowski, 2004) (Eppich, 2004). Some of these sources listed energy inputs directly in terms of energy per unit mass of material processed; these data were used in simulations without any further modification. Some sources did not give the value for energy per unit mass of material processed, but nonetheless supplied data such that it could be calculated easily: the DOE-Rutgers database, for instance, gives data on the total amount of material processed by an operation over a certain period of time, as well as the total energy used in the operation over that time; dividing the latter by the former provides a good estimate of the desired value, often in good agreement with data on the same process from other sources. However, in some cases, data on energy inputs was given in terms of the amount of fuel used, e.g. cubic meters of natural gas or kilograms of coal per unit mass of material processed. The conversion factors used to estimate energy from these sources are listed in Table 1 below.

Fuel Input	Equivalent Energy
1 Liter Gasoline	32.1 MJ
1 Liter Diesel	35.8 MJ
1 Kilogram Bituminous Coal	27 MJ
1 Cubic Meter Natural Gas at STP	38.2 MJ

Table 1 Conversion factors from fuel inputs to the energy they provide. Data from MIT Energy Club Units & Conversions Fact Sheet (Supple, 2007).

While the structured underspecification framework provides an organized way to estimate uncertainty at lower fidelity levels, uncertainty must also be accounted for at L5, the highest fidelity level. The standard deviations for the L5 data points were determined through a pedigree matrix which scores data based on certain criteria (Table 2).

Score	1	2	3	4	5
U1 - Reliability	1.00 – Verified data based on measurements	1.05 – Verified data partly based on assumptions or non-verified data based on measurements	1.10 – Non-verified data partly based on qualified estimates	1.20 – Qualified estimate (e.g. by industry expert) derived from theoretical information	1.50 – Non-qualified estimate
U2 – Completeness	1.00 – Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	1.02 – Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	1.05 – Representative data from only some sites (<<50%) relevant for the market considered OR >50% of sites but from shorter periods	1.10 – Representative data from only one site relevant for the market considered OR some sites but from shorter periods	1.20 – Representativeness unknown or data from a small number of sites AND from shorter periods
U3 – Temporal correlation	1.00 – Less than 3 years of difference to current year	1.03 – Less than 6 years of difference to current year	1.10 – Less than 10 years of difference to current year	1.20 – Less than 15 years of difference to current year	1.50 – Age of date unknown, or more than 15 years of difference to current year
U4 – Geographical correlation	1.00 – Data from area under study	1.01 – Average data from larger area in which the area under study is included	1.02 – Data from smaller area than area under study, or from similar area		1.10 – Data from unknown OR distinctly different area (ex. North America instead of middle east)
U5 – Further Technological correlation	1.00 - Data from enterprises, processes, and materials under study		1.20 - Data on related processes or materials but same technology	1.50 - Data on related processes or materials but different technology	2.00 – Data on related processes or materials but on laboratory scale of different technology
U6 – Sample Size	>100, continuous measurement, balance of purchased products	>20	>10, aggregated figure in environmental report	>=3	Unknown

Table 2 The six scoring factors and criteria used to determine standard deviations (Frischknecht, 2007).

All data entries were evaluated according to this pedigree matrix; as this scoring system is quite commonplace in the field of life cycle assessment, some data entries came with scoring information. The remaining entries were scored according to the judgment of the author. Once quality numbers were assigned, standard deviations were calculated according to

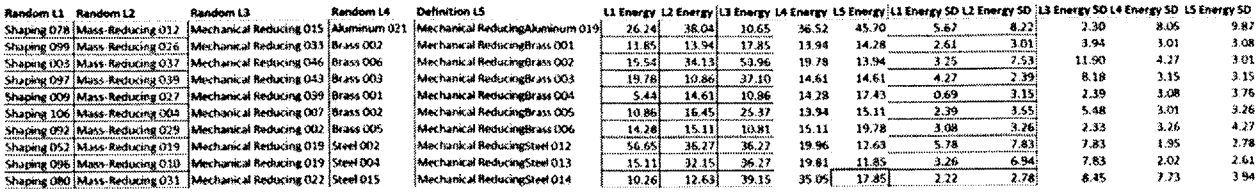
$$SD = \sigma^2 = \exp^{\sqrt{(\ln(U1))^2+(\ln(U2))^2+(\ln(U3))^2+(\ln(U4))^2+(\ln(U5))^2+(\ln(U6))^2}} \qquad Equation\ 1$$

The original data entries were then multiplied by the standard deviation calculated through Equation 1. These deviations were added to the database with their respective data entries. Lognormal distributions were assumed for all L5 entries.

2.2 Simulations to Test Classification Hierarchies

The collected data entries put into a database at L5, and different possibilities for higher-order classification levels were assigned. Monte Carlo simulations were performed in Microsoft Excel using Oracle's Crystal Ball add-in to assess the merits of various classification hierarchies.

A Microsoft Excel spreadsheet was set up such that when the author input a specific L5 entry, the program would match it with the database entry, and recognize all levels of its classification scheme. Excel would fetch the energy and standard deviation for that specific entry, and then, using the RANDBETWEEN function, select random entries from that process's L1-L4 classifications, and then fetch the energies and standard deviations for those random entries. For instance, if the user input "steel forging" as an L5 entry, the program would not only retrieve its energy and standard deviation, but also recognize its L4 as "forging", then retrieve energy and standard deviation for a random process with L4 "forging," and so on for higher levels. Figure 4 shows the interface and its outputs.



Random L1	Random L2	Random L3	Random L4	Definition L5	L1 Energy	L2 Energy	L3 Energy	L4 Energy	L5 Energy	L1 Energy SD	L2 Energy SD	L3 Energy SD	L4 Energy SD	L5 Energy SD
Shaping 078	Mass-Reducing 012	Mechanical Reducing 015	Aluminum 021	Mechanical ReducingAluminum 019	26.24	38.04	10.65	36.52	45.70	5.67	8.22	2.30	8.05	9.87
Shaping 099	Mass-Reducing 026	Mechanical Reducing 033	Brass 002	Mechanical ReducingBrass 001	11.85	13.94	17.85	13.94	14.28	2.61	3.01	3.94	3.01	3.08
Shaping 003	Mass-Reducing 037	Mechanical Reducing 046	Brass 006	Mechanical ReducingBrass 002	15.54	34.13	53.96	19.78	13.94	3.25	7.53	11.90	4.27	3.01
Shaping 097	Mass-Reducing 039	Mechanical Reducing 043	Brass 003	Mechanical ReducingBrass 003	19.78	10.86	37.10	14.61	14.61	4.27	2.39	8.18	3.15	3.15
Shaping 009	Mass-Reducing 027	Mechanical Reducing 039	Brass 001	Mechanical ReducingBrass 004	5.44	14.61	10.86	14.28	17.43	0.69	3.15	2.39	3.08	3.76
Shaping 106	Mass-Reducing 004	Mechanical Reducing 007	Brass 002	Mechanical ReducingBrass 005	10.86	16.45	25.37	13.94	15.11	2.39	3.55	5.48	3.01	3.26
Shaping 092	Mass-Reducing 029	Mechanical Reducing 002	Brass 005	Mechanical ReducingBrass 006	14.28	15.11	10.81	15.11	19.78	3.08	3.26	2.33	3.26	4.27
Shaping 052	Mass-Reducing 019	Mechanical Reducing 019	Steel 002	Mechanical ReducingSteel 012	56.65	36.27	36.27	19.96	12.63	5.78	7.83	7.83	1.95	2.78
Shaping 096	Mass-Reducing 010	Mechanical Reducing 019	Steel 004	Mechanical ReducingSteel 013	15.11	32.15	36.27	19.81	11.85	3.26	6.94	7.83	2.02	2.61
Shaping 080	Mass-Reducing 031	Mechanical Reducing 022	Steel 015	Mechanical ReducingSteel 014	10.26	12.63	39.15	35.05	17.85	2.22	2.78	8.45	7.73	3.94

Figure 4 The Microsoft Excel interface used to generate values to input for simulations.

In a typical trial, the Crystal Ball add-in would take in each energy and standard deviation, and output an energy value from the lognormal distribution. 1000 trials were performed for each L5 entry; it is pertinent to note that for each trial, the random selections for L1-L4 values corresponding to an L5 entry's hierarchy were reset and randomized again.

Two key metrics obtained from the simulation data are the Median Absolute Deviation (MAD) and the Median Absolute Deviation-Coefficient of Variation (MAD-COV). The MAD, represented by Equation 2,

$$MAD = median_i\left(\left|X_i - median_j(X_j)\right|\right) \qquad \text{Equation 2}$$

is obtained by first taking the median of all trial values, then taking the absolute value of the difference between that median and a trial value for all trial values. The median of the resulting set of values is the MAD, which gives information about the distribution of data in the set. Compared to the standard deviation, this value is less affected by outliers. The MAD-COV, represented by Equation 3,

$$MAD - COV = \frac{MAD}{median_j(X_j)} \qquad \text{Equation 3}$$

is obtained by dividing the MAD by the median of all trial values. Not only does this metric capture the information about distribution provided by the MAD, but it also presents it in terms of a percentage, which enables comparison across all process energies.

MAD-COV values were obtained from among all trials for each L5 entry and its associated L1-L4 values. The values were averaged for each branch within a level of classification: for instance, since there was only one branch for L1, there was only one average L1 MAD-COV (though, given that 1000 trials were performed for each process, all L1 values were close to this average); since there were two L2 values, there were two average L2 MAD-COV values, etc. Since each L5 entry is an individual datum, no averages were taken for L5; the MAD-COV values for individual L5 entries were used as-is.

Comparison of MAD-COV values across classification levels reveals critical information about the classification hierarchy. Ideally, the greater underspecification at higher-order levels should translate to higher MAD-COV values than those of more specified levels. If, for a certain classification hierarchy, the MAD-COV increases when moving from lower-fidelity to higher-fidelity levels, the hierarchy does not exhibit characteristics suitable for probabilistic life cycle assessment. New hypotheses must be formulated to improve the classification system. In some cases, the issue may be resolved by switching levels to specify certain characteristics before others. Other instances might require deeper analysis of the processes involved: perhaps there is something inherent in the nature of a certain group of processes that would make another type of classification more favorable.

3. Results and Analysis

A classification hierarchy system for manufacturing processes common to metals with multiple levels of specification was developed. Drawing from a database of energy inputs for 113 different processes, the system was refined through multiple hypotheses and tests such that more underspecified levels had higher MAD-COV values, while still maintaining an organized structure. The complete classification hierarchies for all tests are in the Appendix.

3.1 Inspiration for Hierarchy System, and Its Limitations

The hierarchy expounded in *Manufacturing Process Reference Guide* (Todd, Allen, & Alting, 1994), which logically branches out types of manufacturing processes into more specific ones, serves as the basis for the hierarchies tested in this research (Figure 5).

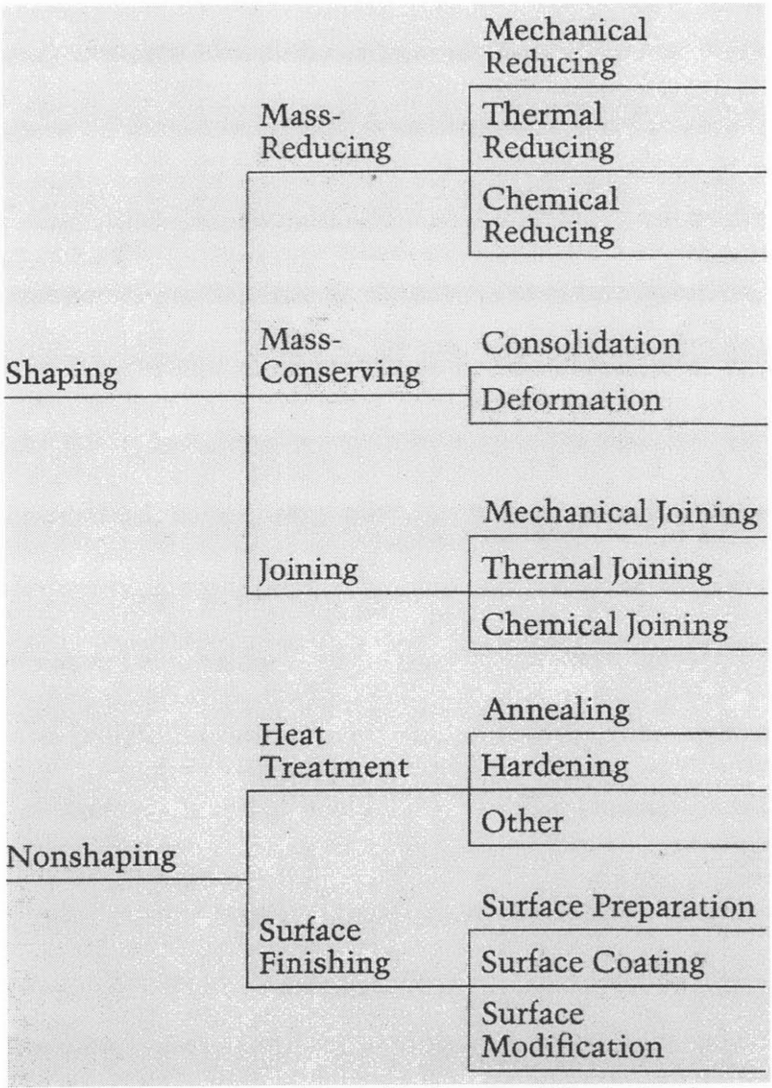


Figure 5 The basis for hierarchies used in this research. Shaping/nonshaping corresponds to level L1, while the branches beneath them correspond to L2, and the branches below those correspond to L3. More specified levels not shown. Adapted from Todd, Allen, and Alting, 1994.

However, numerous changes were made to adapt this hierarchy to the purposes and limitations of this work. Many branches of the hierarchy could not be satisfactorily completed owing to a limited number of data points. Although several sources for process data were consulted, data simply weren't available for several processes, or were only available for such a small portion of a branch (one or two points) that including it in tests wouldn't provide meaningful information about the usefulness of the classification.

Furthermore, even in some instances where data could be acquired, it turned out that the units were incompatible with the simulations: consider many chemical processes, which often involve the coating of metal surfaces. Naturally, data for these processes comes in units of energy per surface area, as opposed to energy per mass of metal processed. Theoretically, given the density of the metal and the processing rate, one could convert these data into units of energy per mass, but as the processing rate varies from operation to operation, and may indeed be dictated by additional factors (e.g. processing rates limited by material properties, or economic conditions driving the rate at which a factory conducts its operations), it would be cumbersome and of limited utility to try to include these data points in simulations. Ultimately, it may not make sense to deal with such processes in terms of energy per kilogram of material processed. Perhaps it would be useful to develop a separate classification hierarchy system for processes best represented in units of energy per unit area. Such a construction, however, is beyond the scope of the current research.

As this research was significantly impacted by the availability of data, only a few branches were thoroughly completed. For this reason, early experimental simulations focused on lower-order levels, neglecting L1 and L2 in favor of refining the L3 categories of deformation, consolidation, mechanical reducing, and the branches underneath them. After these L3 categories were sufficiently refined, attempts were made to incorporate them in a broad, overarching hierarchy including levels L1 and L2.

3.2 Developing the Deformation Branch

The branch of processes categorized as deformation was the first to be explored. Starting with deformation at L3, processes were differentiated into forging, extruding, wire drawing, and sheet rolling at L4. L5 consisted of the individual data points gathered for various processes (e.g. steel forging, aluminum forging, copper wire drawing, etc.). A numerical breakdown of the deformation categories is show in Table 3 below. The complete list of deformation categories and processes is in Appendix A.1.

Level	Categories
L3	1
L4	4
L5	25

Table 3 Number of categories for the branches underneath L3 category "deformation."

The MAD-COV averages were calculated for each classification in each level and plotted in Figure 6 below. As the figure shows, the MAD-COV starts out at around 69% for L3, then decreases for each successive level, varying from 43% to 66% for the four L4 categories, and varying from 6% to 42% across the 25 entries for L5. In all cases, the MAD-COV decreased as specification of the process increased, demonstrating the viability of this classification scheme for life cycle assessment of these deformation processes.

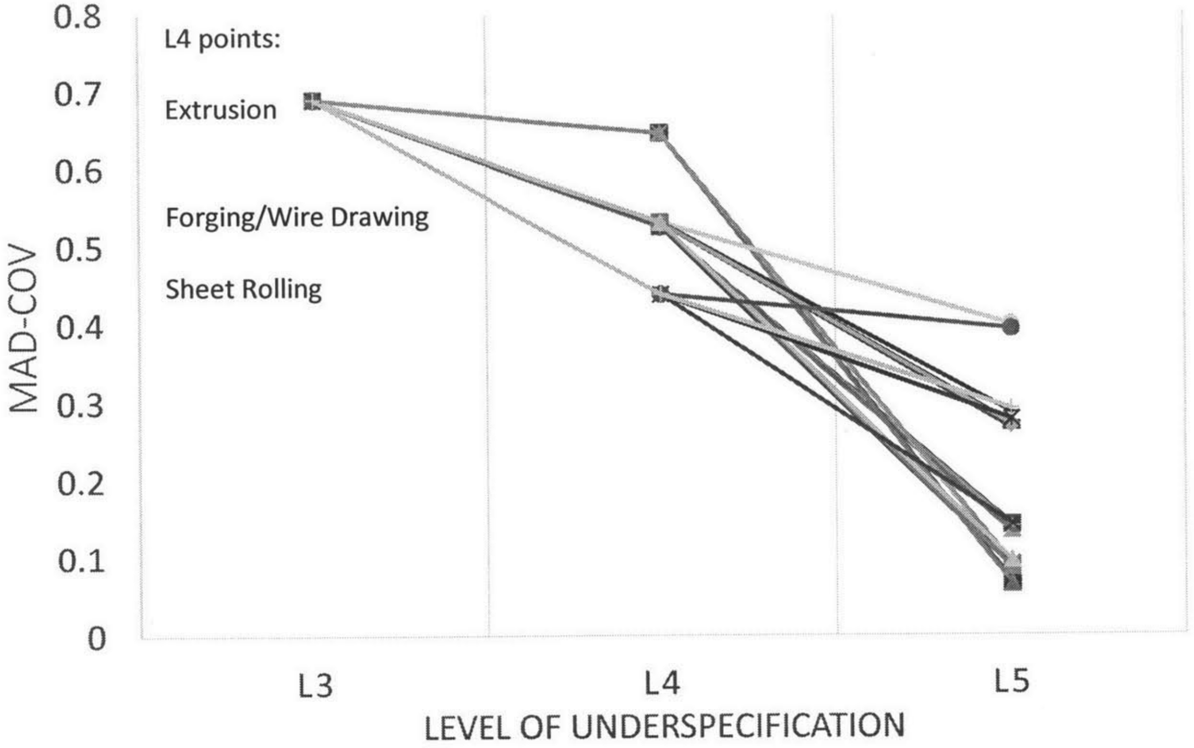


Figure 6 MAD-COV averages for deformation L3.

Another classification system was explored with deformation at L3, which can be found in Appendix A.2. To investigate at which point it becomes useful to define material type, L4 was changed to consist of aluminum, steel, and copper, while actual deformation processes were defined by individual entries at L5. MAD-COV values for simulations with this hierarchy are plotted in Figure 7.

This classification scheme was not as effective as the other one for L3 deformation. L4 MAD-COVs were higher than the L3 MAD-COV for steel and aluminum, demonstrating that this classification is not favorable for probabilistic LCA involving those materials. However, this was not the case for copper, which exhibited a lower MAD-COV at L4 than at L3. This could be due to a number of reasons, the most likely being the amount of data points and the processes covered. Entries with copper L4 only constituted five of the 25 data points in deformation L3, with aluminum and steel covering the rest. Moreover, four of the five copper entries were for wire drawing; it is not surprising that there is less variation within this category as compared to steel and aluminum, which have multiple entries for a greater diversity of processes. The lower MAD-COV for L4 copper might also be related to its material properties. Owing to the high ductility of copper, it is possible that the energies to deform it are low in general, and therefore have a smaller distribution than processes on aluminum and steel, which may have a larger range of input energies depending on how they are deformed. The more likely explanation is that the variation is caused by fewer and less diverse entries for copper, but it might be pertinent to do further investigation on how materials properties could affect distribution.

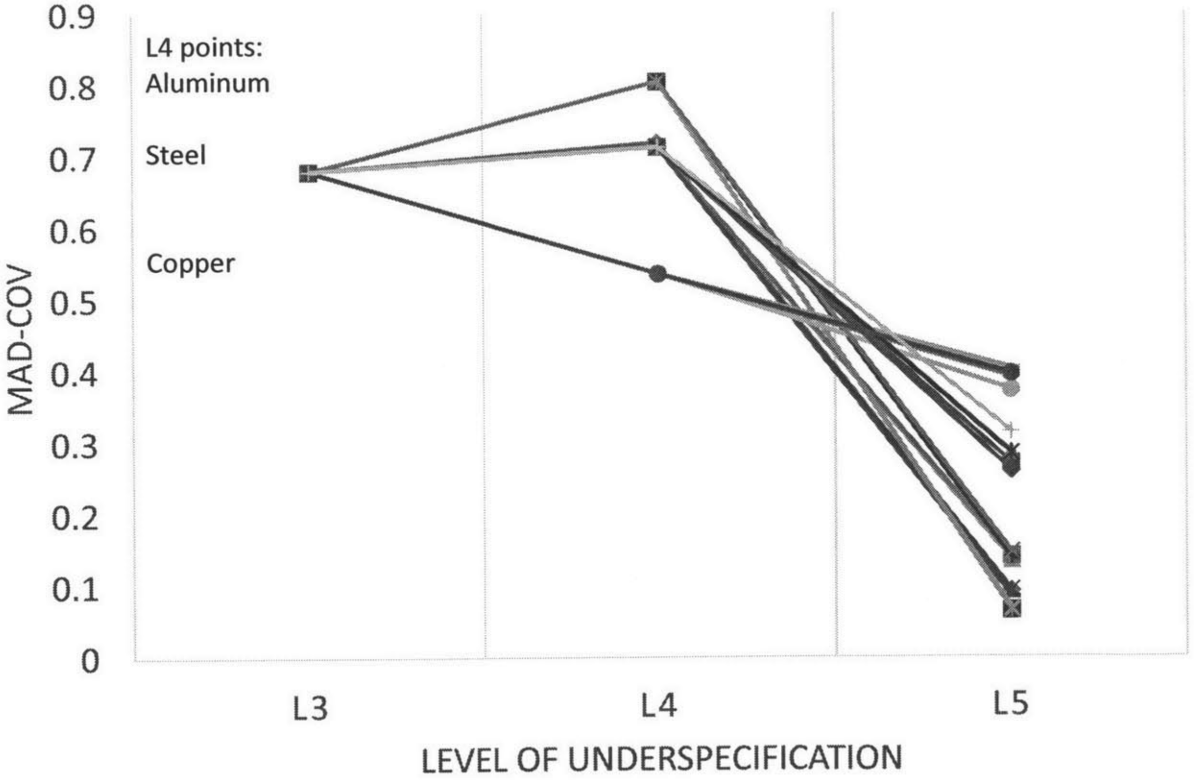


Figure 7 MAD-COV averages for deformation L3 with metal type L4.

3.3 Developing the Consolidation Branch

Consolidation was the next branch to be developed. Originally, the goal was to break down the consolidation L3 into various types of casting (investment, sand, die, lost foam, etc.) at L4, with individual entries at L5. This could not be carried out due to limitations in data availability; for instance, there was only one entry on lost foam casting, rendering such an L4 classification superfluous. In another case, the author was unsure whether 'high pressure die casting' would best be grouped with die casting or on its own; in the latter case, it would again incur the issue of an L4 classification functionally identical to an L5 entry. Of the processes with more than one data point, there tended to be an abundance for a certain metal type – the vast majority of points for die casting were aluminum die casting, which would skew a process-based classification at L4 towards aluminum values. Overall, this proposed classification proved inadequate before simulations were even performed.

Naturally, then, the alternative is to classify by metal type at L4. Consolidation was broken down into aluminum, gray and ductile iron, magnesium, steel, zinc, copper, iron, and titanium. Table 4 shows the category breakdown by level for a total of 42 L5 entries. The complete consolidation hierarchy is the consolidation branch in Appendix A.1.

Level	Categories
L3	1
L4	8
L5	42

Table 4 Number of categories for the branches underneath L3 category "consolidation."

Results of trial simulations are plotted in Figure 8 below, with labels along the Y axis in descending order to indicate which points correspond to different L4 categories.

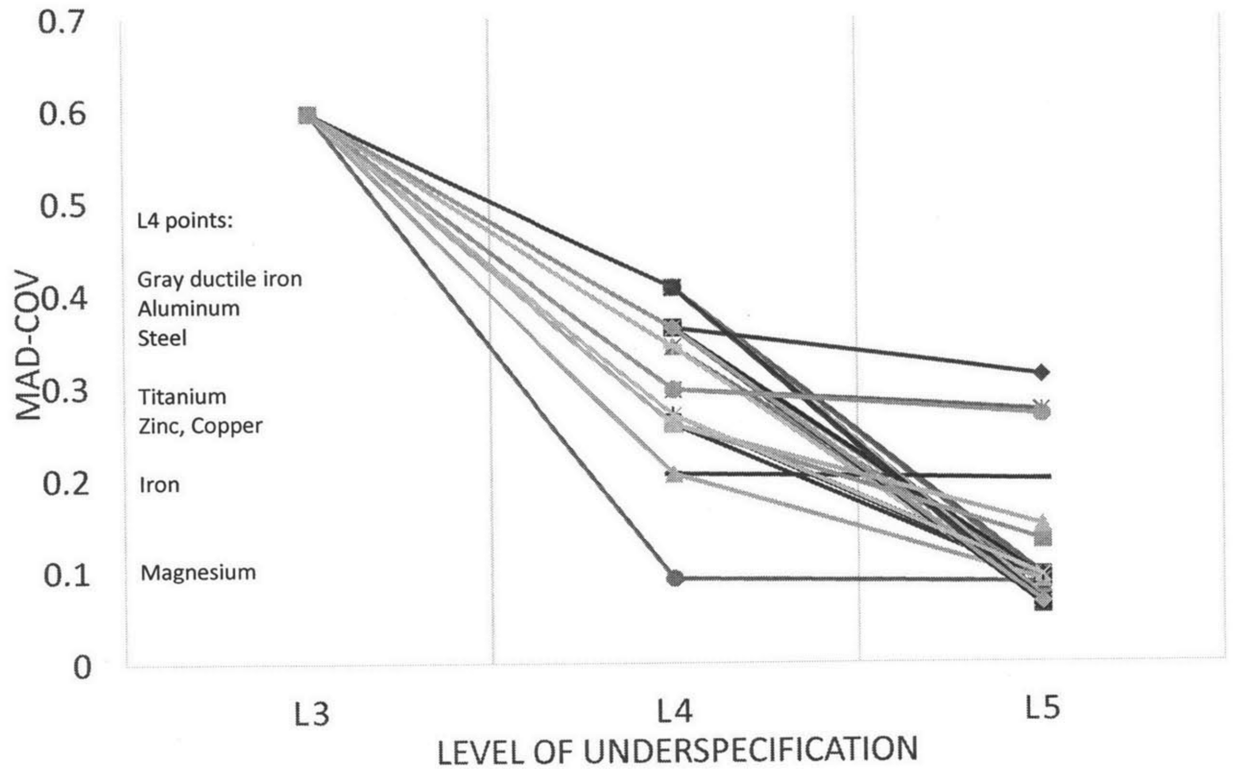


Figure 8 MAD-COV averages for consolidation L3.

As the plot shows, this classification scheme does a good job at representing underspecification for consolidation processes. All points at L4 have a lower MAD-COV than L3, and the points at L5 are either lower than or nearly equal to the points at L4. However, while this hierarchy may very well be useful, it is pertinent to understand to what extent the number of data points may influence MAD-COV values. Table 5 lists the number of data points underneath each L4 classification. In the obvious cases of magnesium and titanium, it would be premature to conclude the effectiveness of this system due to the limited number of data points. It is also no surprise that aluminum and gray and ductile iron have higher MAD-COV values; there were several entries for these materials, retrieved from a diversity of operations, some of which were orders of magnitude different in their scale.

L4 Category	Number of Entries in L5
Magnesium	1
Titanium	2
Iron	2
Copper	3
Zinc	3
Steel	5
Gray and Ductile Iron	13
Aluminum	13

Table 5 Number of L5 entries per L4 category.

There are some more issues with the general validity of this classification system. Additional data on other types of casting could potentially raise MAD-COV values such that they are higher for L4 than for L3. For instance, the aluminum data are disproportionately for aluminum die casting, the individual entries for which make up 8 of the 13 aluminum entries. If more data were acquired such that other types of aluminum casting were better represented, depending on the energies of the added processes, the aluminum L4 MAD-COV could go from its already high value to a point which would render the classification invalid. For this reason, future research should focus on the acquisition of more data points, keeping open the possibility for alternative classifications (e.g. casting type at L4). Nonetheless, within the context of the current work, it appears that specifying metal type for casting operations will aid in probabilistic life cycle assessment.

3.4 Developing the Mechanical Reducing Branch

The third and final smaller branch completed was a set of processes grouped together as mechanical reducing at L3. The hierarchy in *Manufacturing Process Reference Guide* divides mechanical reducing into two parts used as L4 categories, single-point cutting and multi-point cutting. Data were obtained for the energies of different types of milling and turning for various metals for a total of 46 L5 entries. MAD-COV values obtained from test simulations are plotted in Figure 9. The initial hierarchy is presented in full in Appendix A.3.

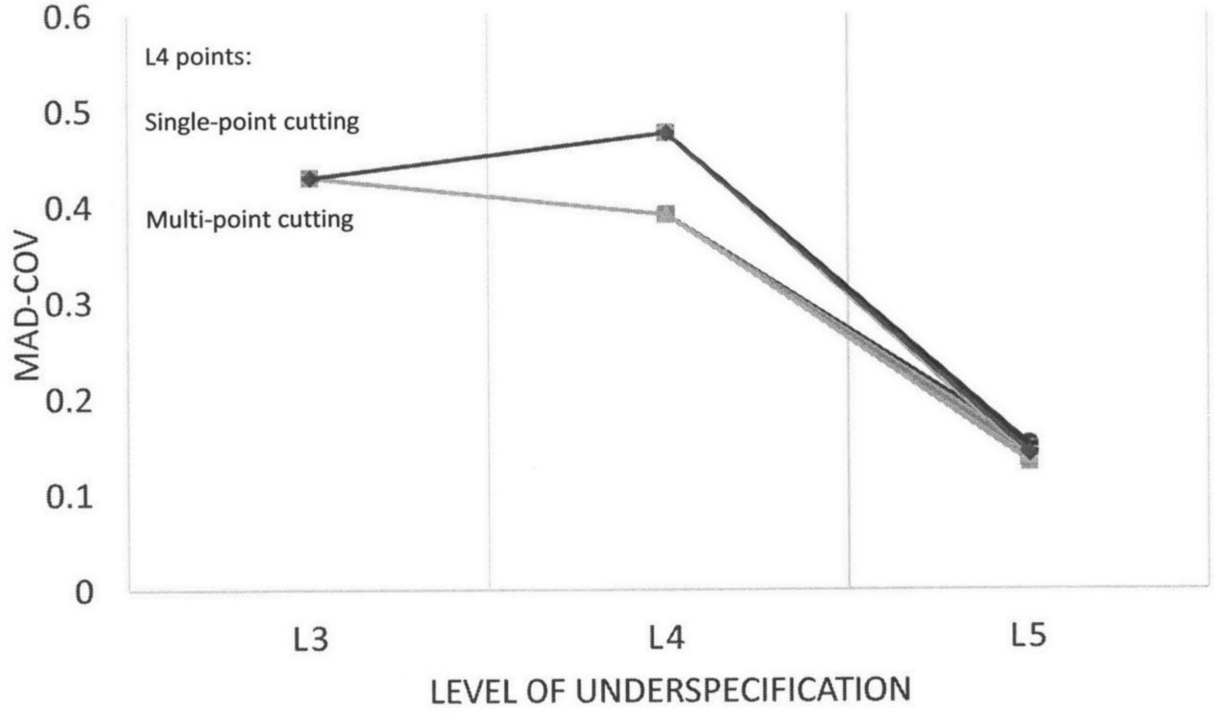


Figure 9 MAD-COV averages for mechanical reducing L3 with cutting distinction L4.

It is apparent that specifying single versus multi point cutting at L4 would not be very effective for probabilistic analysis, as multi-point cutting has greater variation than the mechanical reducing L3. Alternative classifications were investigated for the L4. The obvious alternative for the available data points would be a distinction between turning and milling, but as all turning entries were single-point cutting and all milling entries were multi-point cutting, this would have produced the exact same results. Instead, metal type was selected to specify L4, with milling and turning grouped together for each metal. Table 6 displays the number of categories for each level of underspecification. The hierarchy investigated is the Mechanical Reducing branch in Appendix A.1.

Level	Categories
L3	1
L4	5
L5	46

Table 6 Number of categories for the branches underneath L3 category "mechanical reducing."

Simulations were tested using the new L4 classifications, the results of which are displayed in Figure 10. This turns out to be a much better distinction than single versus multi point cutting. MAD-COV values decrease from around 43% at L3 to a range of 17% through 23% at L4, and then decrease even further for individual L5 entries. Results are unlikely to be significantly influenced by quantity or quality of entries; all metal types have 10 entries, with the exception of brass (which has 6), and all cover both turning and milling processes, except for brass (which only covers turning).

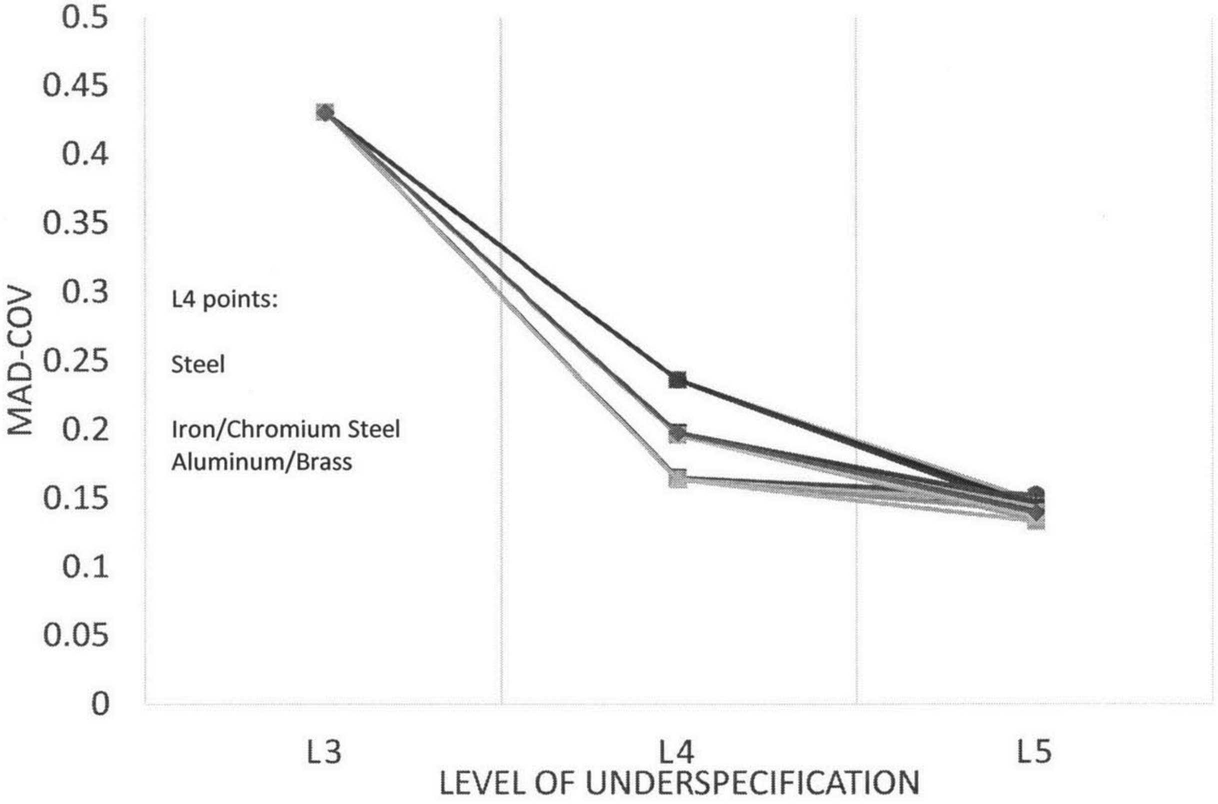


Figure 10 MAD-COV averages for mechanical reducing L3 with metal type L4.

It appears that specifying metal type for mechanical reducing processes could indeed reduce uncertainty for probabilistic LCA. This is fairly intuitive, as mechanical reduction of material mass will likely be dictated by various moduli unique to each material. However, as with the previously developed branches, more data points for additional processes would be helpful in determining just how useful this classification is.

3.5 Assembling Smaller Branches Into a Larger Hierarchy

With three branches sufficiently completed at the L3, a first attempt was made at putting all data into a complete hierarchy of five levels. The hierarchy was structured as in Figure 5, putting consolidation and deformation under L2 category 'mass conserving,' while placing mechanical reducing under 'mass reducing.' No further modifications were made; Section A1 shows the five-level hierarchy in full. 1000 trials were conducted for each process entry to acquire MAD-COV values for all levels of underspecification. Results are plotted in Figure 11.

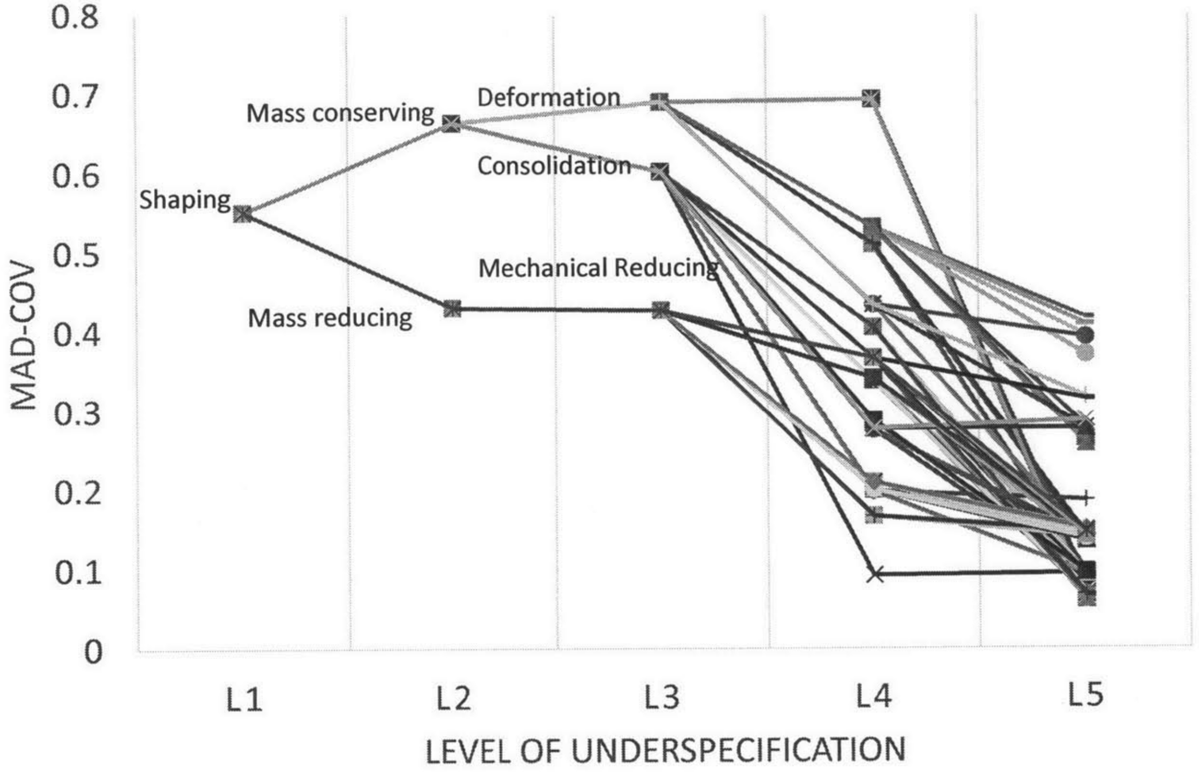


Figure 11 MAD-COV averages for entire initial classification hierarchy.

As is plainly evident, simply grouping processes according to the textbook hierarchy does not reflect a decreasing uncertainty for each successive level: the all-encompassing 'shaping' L1 category has a lower MAD-COV than two of the three L3 branches, while the grouping of consolidation and deformation under 'mass conserving' does not result in a classification with general decreased uncertainty for increased specificity. Moreover, as the only branch of mass reducing is mechanical reducing, their L2 and L3 values are the same. It is clear that the system must be altered and refined for a five level classification to be useful.

3.6 Modifying the Hierarchy to Differentiate by Metal Type at L1 and L2

Since defining metal type often improved results for lower branches, an important test for a five-level hierarchy is which level would be best to make this specification. As the initial L1 and L2 classifications were not productive towards the end of this research, the hierarchy was modified to define metal type at those levels. This change enabled and required some modifications to already existing branches: for instance, with the consolidation branch underneath metal type, all MAD-COV values for L4 category 'aluminum casting' would be equivalent to L3 category 'aluminum consolidation.' However, whereas previously, grouping by specific types of casting was avoided because it tended to skew results in favor of one metal, it was not an issue in this case because metal type had already been defined. Thus, where it could be done, casting type was defined at L4. In instances where there was only one entry for a specific casting type, it was simply repeated for both L4 and L5. The complete modified classification hierarchies introducing metal type at L1 and L2 can be found in Appendix A.4 and A.5.

Trials were conducted to test the effectiveness of the new hierarchies. MAD-COV values are displayed in Figure 12. Figure 12.a plots the results for defining metal type at L1. This classification actually proved worse than the initial one – L1 MAD-COV values were lower than L2 MAD-COVs for all categories, as well as some L3 values. As it may be difficult to determine individual categories from the chart, select L1 and L2 MAD-COV values are displayed in Table 7. This category breakdown suffered from a similar problem as the initial hierarchy, namely, a split between relatively higher MAD-COV values for mass-conserving L2 categories and relatively lower MAD-COV values for mass-reducing L2 categories. In other cases, MAD-COV values remained the same across multiple levels.

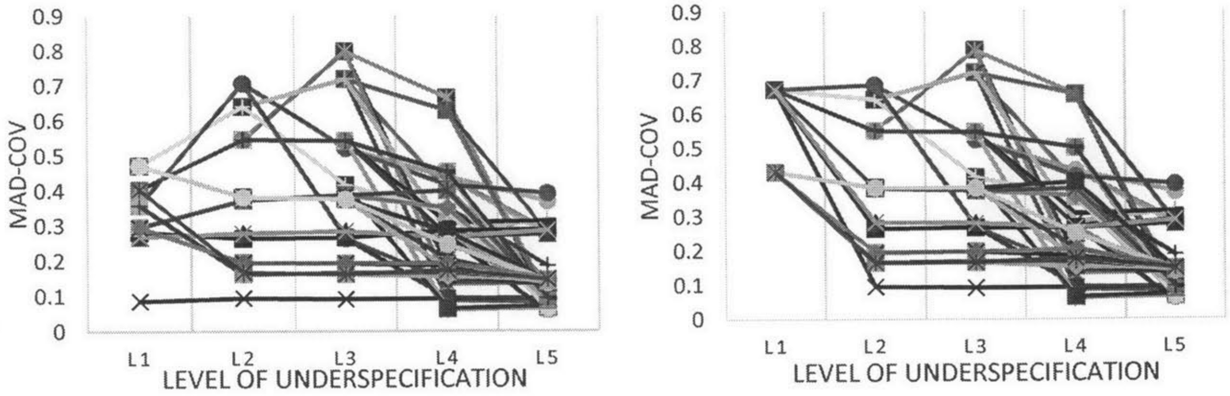


Figure 12 Left: MAD-COV averages for classification hierarchy with L1 metal type. Right: MAD-COV averages for classification hierarchy with L2 metal type.

L1 category	L1 MAD-COV average	L2 category	L2 MAD-COV average
Steel	0.47	Steel mass-conserving	0.64
		Steel mass-reducing	0.38
Aluminum	0.40	Aluminum mass-conserving	0.55
		Aluminum mass-reducing	0.17
Copper	0.36	Copper mass-conserving	0.71
		Copper mass-reducing	0.16
Iron	0.30	Iron mass-conserving	0.37
		Iron mass-reducing	0.2

Table 7 MAD-COV values for classification hierarchy with metal type defined at L1, showing split between mass-conserving and mass-reducing at L2.

It makes little sense to group mass-conserving and mass-reducing under the same higher-order category, at least with the data currently available. When refining the hierarchy to specify metal type at L2, therefore, the distinction between mass-conserving and mass-reducing was made at the L1. Figure 12.b plots the MAD-COV values by level for this second modified hierarchy. Compared to the previous two attempts, this classification scheme appears to be better suited for probabilistic life cycle assessment, as a good amount of MAD-COV values at more specified levels are lower than those at less specified levels. However, for both hierarchies defining metal type at higher order classifications, certain drawbacks are apparent. The higher MAD-COV values at L3 correspond to deformation processes, which, as demonstrated in

Section 3.2, are better specified by process type than metal type. Indeed, these higher values can be attributed to the large number of entries for steel and aluminum deformation processes, which cover small to large operations and have a lot of variation. At this point, a large classification hierarchy does not yet appear to be viable for probabilistic life cycle assessment, at least for the branches of processes and data entries collected for this work.

4. Conclusions and Future Work

This thesis investigates the viability of adapting probabilistic underspecification methods for life cycle assessment to industrial processes on metals. Previously established methodologies for life cycle assessment of products are analyzed and modified towards this end. Data on the energy inputs for several industrial processes were used to construct classification hierarchies, which were then tested with Monte Carlo simulation to obtain MAD-COV values, which led to the formation of new classification hypotheses and further testing.

These results indicate that realization of a broad hierarchy for a wide variety of materials processes is not on the immediate horizon. MAD-COV values for all proposed hierarchies for the given data points were scattered, and often higher at more specified levels, rendering them unsuitable for probabilistic life cycle assessment. Nonetheless, it is remarkable that for smaller branches consisting of only three levels of underspecification, MAD-COV values decreased as specification increased, suggesting that multiple smaller hierarchies may more effectively address the issue of uncertainty with process-based LCA. Indeed, there is no inherent demand to branch all material processes under the same hierarchy.

Of course, these results apply mainly to the entries on process energy collected for this research, and may not necessarily hold up as more processes and branches are added. While this work included data points on several processes, it only captures a fraction of the proposed general hierarchy, let alone the actual breadth of industrial process energies. This was noted in the analysis of all proposed hierarchies; additional hypotheses were suggested in case more database entries invalidated the current system. Future work should therefore focus on acquiring more data, expanding existing hierarchies, revisiting some discarded hierarchies, and even developing new ones.

Even though the results of this work may require modification to accommodate for additional data and processes, they represent an important foray into the field of process-based life cycle assessment. The methodology developed herein may be adapted to industrial processes for other materials, such as plastics and metals. Further research in this field has significant potential to change the operation of certain facilities, if not entire industries, and may eventually reduce the impact of industrial processing on the environment.

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6. Appendix

A.1 Complete Hierarchy of Levels and Processes – Initial Test

L1	L2	L3	L4	L5
Shaping	Mass-Conserving	Deformation	Forging	carbon and alloy steel forgings
Shaping	Mass-Conserving	Deformation	Forging	steel forgings
Shaping	Mass-Conserving	Deformation	Forging	steel forgings
Shaping	Mass-Conserving	Deformation	Forging	steel forgings

Shaping	Mass-Conserving	Deformation	Forging	steel forging
Shaping	Mass-Conserving	Deformation	Forging	steel forgings
Shaping	Mass-Conserving	Deformation	Forging	aluminum forgings
Shaping	Mass-Conserving	Deformation	Forging	aluminum forgings
Shaping	Mass-Conserving	Deformation	Extrusion	steel extrusion
Shaping	Mass-Conserving	Deformation	Extrusion	aluminum extrusions
Shaping	Mass-Conserving	Deformation	Extrusion	aluminum extrusions
Shaping	Mass-Conserving	Deformation	Extrusion	aluminum extrusions
Shaping	Mass-Conserving	Deformation	Extrusion	aluminum extrusions
Shaping	Mass-Conserving	Deformation	Extrusion	aluminum extrusions
Shaping	Mass-Conserving	Deformation	Wire Drawing	copper wire drawing
Shaping	Mass-Conserving	Deformation	Wire Drawing	copper wire drawing
Shaping	Mass-Conserving	Deformation	Wire Drawing	copper wire drawing
Shaping	Mass-Conserving	Deformation	Wire Drawing	copper wire drawing
Shaping	Mass-Conserving	Deformation	Wire Drawing	steel wire drawing
Shaping	Mass-Conserving	Deformation	Wire Drawing	steel wire drawing
Shaping	Mass-Conserving	Deformation	Wire Drawing	steel wire drawing
Shaping	Mass-Conserving	Deformation	Sheet Rolling	aluminum sheet rolling
Shaping	Mass-Conserving	Deformation	Sheet Rolling	chromium steel sheet rolling
Shaping	Mass-Conserving	Deformation	Sheet Rolling	copper sheet rolling
Shaping	Mass-Conserving	Deformation	Sheet Rolling	steel sheet rolling
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray iron casting
Shaping	Mass-Conserving	Consolidation	gray ductile iron	ductile iron pipe casting
Shaping	Mass-Conserving	Consolidation	steel	steel casting
Shaping	Mass-Conserving	Consolidation	aluminum	high pressure aluminum die casting

Shaping	Mass-Conserving	Consolidation	aluminum	aluminum sand casting
Shaping	Mass-Conserving	Consolidation	magnesium	magnesium die casting
Shaping	Mass-Conserving	Consolidation	zinc	zinc die casting
Shaping	Mass-Conserving	Consolidation	copper	copper sand casting
Shaping	Mass-Conserving	Consolidation	iron	iron sand casting
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum lost foam casting
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum sand casting
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum casting
Shaping	Mass-Conserving	Consolidation	steel	steel casting
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum die castings
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray iron
Shaping	Mass-Conserving	Consolidation	steel	steel and iron castings
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum die castings
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray and ductile iron castings
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum die castings
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray and ductile iron castings
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray iron castings
Shaping	Mass-Conserving	Consolidation	steel	steel investment castings
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray and ductile castings
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray iron castings
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum die castings
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray and ductile castings
Shaping	Mass-Conserving	Consolidation	steel	steel castings
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum die castings
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray and ductile castings

Shaping	Mass-Conserving	Consolidation	iron	iron sand castings
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray and ductile iron castings
Shaping	Mass-Conserving	Consolidation	zinc	zinc die casting
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray and ductile iron castings
Shaping	Mass-Conserving	Consolidation	gray ductile iron	gray and ductile iron castings
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum die castings
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum die castings
Shaping	Mass-Conserving	Consolidation	aluminum	aluminum die castings
Shaping	Mass-Conserving	Consolidation	copper	brass castings
Shaping	Mass-Conserving	Consolidation	copper	brass castings
Shaping	Mass-Conserving	Consolidation	zinc	zinc die casting
Shaping	Mass-Conserving	Consolidation	titanium	titanium castings
Shaping	Mass-Conserving	Consolidation	titanium	titanium castings
Shaping	Mass-Reducing	Mechanical Reducing	Steel	Turning steel, conventional, average
Shaping	Mass-Reducing	Mechanical Reducing	Steel	Turning steel, conventional, primarily roughing
Shaping	Mass-Reducing	Mechanical Reducing	Steel	Turning steel, conventional, primarily dressing
Shaping	Mass-Reducing	Mechanical Reducing	Steel	Turning steel, CNC, average
Shaping	Mass-Reducing	Mechanical Reducing	Steel	Turning steel, CNC, primarily roughing
Shaping	Mass-Reducing	Mechanical Reducing	Steel	Turning steel, CNC, primarily dressing
Shaping	Mass-Reducing	Mechanical Reducing	Chromium Steel	Turning chromium steel, conventional, average
Shaping	Mass-Reducing	Mechanical Reducing	Chromium Steel	Turning chromium steel, conventional, primarily roughing
Shaping	Mass-Reducing	Mechanical Reducing	Chromium Steel	Turning chromium steel, conventional, primarily dressing
Shaping	Mass-Reducing	Mechanical Reducing	Chromium Steel	Turning chromium steel, CNC, average
Shaping	Mass-Reducing	Mechanical Reducing	Chromium Steel	Turning chromium steel, CNC, primarily roughing
Shaping	Mass-Reducing	Mechanical Reducing	Chromium Steel	Turning chromium steel, CNC, primarily dressing
Shaping	Mass-Reducing	Mechanical Reducing	Iron	Turning cast iron, conventional, average

Shaping	Mass-Reducing	Mechanical Reducing	Iron	Turning cast iron, conventional, primarily roughing
Shaping	Mass-Reducing	Mechanical Reducing	Iron	Turning cast iron, conventional, primarily dressing
Shaping	Mass-Reducing	Mechanical Reducing	Iron	Turning cast iron, CNC, average
Shaping	Mass-Reducing	Mechanical Reducing	Iron	Turning cast iron, CNC, primarily roughing
Shaping	Mass-Reducing	Mechanical Reducing	Iron	Turning cast iron, CNC, primarily dressing
Shaping	Mass-Reducing	Mechanical Reducing	Aluminum	Turning aluminum, conventional, average
Shaping	Mass-Reducing	Mechanical Reducing	Aluminum	Turning aluminum, conventional, primarily roughing
Shaping	Mass-Reducing	Mechanical Reducing	Aluminum	Turning aluminum, conventional, primarily dressing
Shaping	Mass-Reducing	Mechanical Reducing	Aluminum	Turning aluminum, CNC, average
Shaping	Mass-Reducing	Mechanical Reducing	Aluminum	Turning aluminum, CNC, primarily roughing
Shaping	Mass-Reducing	Mechanical Reducing	Aluminum	Turning aluminum, CNC, primarily dressing
Shaping	Mass-Reducing	Mechanical Reducing	Brass	Turning brass, conventional, average
Shaping	Mass-Reducing	Mechanical Reducing	Brass	Turning brass, conventional, primarily roughing
Shaping	Mass-Reducing	Mechanical Reducing	Brass	Turning brass, conventional, primarily dressing
Shaping	Mass-Reducing	Mechanical Reducing	Brass	Turning brass, CNC, average
Shaping	Mass-Reducing	Mechanical Reducing	Brass	Turning brass, CNC, primarily roughing
Shaping	Mass-Reducing	Mechanical Reducing	Brass	Turning brass, CNC, primarily dressing
Shaping	Mass-Reducing	Mechanical Reducing	Steel	Milling steel, average
Shaping	Mass-Reducing	Mechanical Reducing	Steel	Milling steel, large parts
Shaping	Mass-Reducing	Mechanical Reducing	Steel	Milling steel, small parts
Shaping	Mass-Reducing	Mechanical Reducing	Steel	Milling steel, dressing
Shaping	Mass-Reducing	Mechanical Reducing	Chromium Steel	Milling chromium steel, average
Shaping	Mass-Reducing	Mechanical Reducing	Chromium Steel	Milling chromium steel, large parts
Shaping	Mass-Reducing	Mechanical Reducing	Chromium Steel	Milling chromium steel, small parts
Shaping	Mass-Reducing	Mechanical Reducing	Chromium Steel	Milling chromium steel, dressing
Shaping	Mass-Reducing	Mechanical Reducing	Iron	Milling cast iron, average
Shaping	Mass-Reducing	Mechanical Reducing	Iron	Milling cast iron, large parts
Shaping	Mass-Reducing	Mechanical Reducing	Iron	Milling cast iron, small parts
Shaping	Mass-Reducing	Mechanical Reducing	Iron	Milling cast iron, dressing
Shaping	Mass-Reducing	Mechanical Reducing	Aluminum	Milling aluminum, average
Shaping	Mass-Reducing	Mechanical Reducing	Aluminum	Milling aluminum, large parts
Shaping	Mass-Reducing	Mechanical Reducing	Aluminum	Milling aluminum, small parts
Shaping	Mass-Reducing	Mechanical Reducing	Aluminum	Milling aluminum, dressing

A.2 Classification Hierarchy for Deformation L3 and Metal Type L4

L3	L4	L5
Deformation	steel	carbon and alloy steel forgings
Deformation	steel	steel forgings
Deformation	steel	steel forgings
Deformation	steel	steel forgings
Deformation	steel	steel forging
Deformation	steel	steel forgings
Deformation	aluminum	aluminum forgings
Deformation	aluminum	aluminum forgings
Deformation	steel	steel extrusion
Deformation	aluminum	aluminum extrusions
Deformation	aluminum	aluminum extrusions
Deformation	aluminum	aluminum extrusions
Deformation	aluminum	aluminum extrusions
Deformation	aluminum	aluminum extrusions
Deformation	copper	copper wire drawing
Deformation	copper	copper wire drawing
Deformation	copper	copper wire drawing
Deformation	copper	copper wire drawing
Deformation	steel	steel wire drawing
Deformation	steel	steel wire drawing
Deformation	steel	steel wire drawing
Deformation	aluminum	aluminum sheet rolling
Deformation	steel	chromium steel sheet rolling
Deformation	copper	copper sheet rolling
Deformation	steel	steel sheet rolling

A.3 Initial Classification Hierarchy for Mechanical Reducing L3

L3	L4	L5
Mechanical Reducing	Single-point cutting	Turning steel, conventional, average
Mechanical Reducing	Single-point cutting	Turning steel, conventional, primarily roughing
Mechanical Reducing	Single-point cutting	Turning steel, conventional, primarily dressing
Mechanical Reducing	Single-point cutting	Turning steel, CNC, average
Mechanical Reducing	Single-point cutting	Turning steel, CNC, primarily roughing
Mechanical Reducing	Single-point cutting	Turning steel, CNC, primarily dressing
Mechanical Reducing	Single-point cutting	Turning chromium steel, conventional, average
Mechanical Reducing	Single-point cutting	Turning chromium steel, conventional, primarily roughing
Mechanical Reducing	Single-point cutting	Turning chromium steel, conventional, primarily dressing

Mechanical Reducing	Single-point cutting	Turning chromium steel, CNC, average
Mechanical Reducing	Single-point cutting	Turning chromium steel, CNC, primarily roughing
Mechanical Reducing	Single-point cutting	Turning chromium steel, CNC, primarily dressing
Mechanical Reducing	Single-point cutting	Turning cast iron, conventional, average
Mechanical Reducing	Single-point cutting	Turning cast iron, conventional, primarily roughing
Mechanical Reducing	Single-point cutting	Turning cast iron, conventional, primarily dressing
Mechanical Reducing	Single-point cutting	Turning cast iron, CNC, average
Mechanical Reducing	Single-point cutting	Turning cast iron, CNC, primarily roughing
Mechanical Reducing	Single-point cutting	Turning cast iron, CNC, primarily dressing
Mechanical Reducing	Single-point cutting	Turning aluminum, conventional, average
Mechanical Reducing	Single-point cutting	Turning aluminum, conventional, primarily roughing
Mechanical Reducing	Single-point cutting	Turning aluminum, conventional, primarily dressing
Mechanical Reducing	Single-point cutting	Turning aluminum, CNC, average
Mechanical Reducing	Single-point cutting	Turning aluminum, CNC, primarily roughing
Mechanical Reducing	Single-point cutting	Turning aluminum, CNC, primarily dressing
Mechanical Reducing	Single-point cutting	Turning brass, conventional, average
Mechanical Reducing	Single-point cutting	Turning brass, conventional, primarily roughing
Mechanical Reducing	Single-point cutting	Turning brass, conventional, primarily dressing
Mechanical Reducing	Single-point cutting	Turning brass, CNC, average
Mechanical Reducing	Single-point cutting	Turning brass, CNC, primarily roughing
Mechanical Reducing	Single-point cutting	Turning brass, CNC, primarily dressing
Mechanical Reducing	Multi-point cutting	Milling steel, average
Mechanical Reducing	Multi-point cutting	Milling steel, large parts
Mechanical Reducing	Multi-point cutting	Milling steel, small parts
Mechanical Reducing	Multi-point cutting	Milling steel, dressing
Mechanical Reducing	Multi-point cutting	Milling chromium steel, average
Mechanical Reducing	Multi-point cutting	Milling chromium steel, large parts
Mechanical Reducing	Multi-point cutting	Milling chromium steel, small parts
Mechanical Reducing	Multi-point cutting	Milling chromium steel, dressing
Mechanical Reducing	Multi-point cutting	Milling cast iron, average
Mechanical Reducing	Multi-point cutting	Milling cast iron, large parts
Mechanical Reducing	Multi-point cutting	Milling cast iron, small parts
Mechanical Reducing	Multi-point cutting	Milling cast iron, dressing
Mechanical Reducing	Multi-point cutting	Milling aluminum, average
Mechanical Reducing	Multi-point cutting	Milling aluminum, large parts
Mechanical Reducing	Multi-point cutting	Milling aluminum, small parts
Mechanical Reducing	Multi-point cutting	Milling aluminum, dressing

A.4 Complete Hierarchy of Levels and Processes – Metal Type at L1

L1	L2	L3	L4	L5
steel	Steel Mass-Conserving	Steel Deformation	Steel Forging	carbon and alloy steel forgings

steel	Steel Mass-Conserving	Steel Deformation	Steel Forging	steel forgings 1
steel	Steel Mass-Conserving	Steel Deformation	Steel Forging	steel forgings 2
steel	Steel Mass-Conserving	Steel Deformation	Steel Forging	steel forgings 3
steel	Steel Mass-Conserving	Steel Deformation	Steel Forging	steel forging
steel	Steel Mass-Conserving	Steel Deformation	Steel Forging	steel forgings 4
aluminum	Aluminum Mass-Conserving	Aluminum Deformation	Aluminum Forging	aluminum forgings
aluminum	Aluminum Mass-Conserving	Aluminum Deformation	Aluminum Forging	aluminum forgings 2
steel	Steel Mass-Conserving	Steel Deformation	Steel Extrusion	steel extrusion
aluminum	Aluminum Mass-Conserving	Aluminum Deformation	Aluminum Extrusion	aluminum extrusions
aluminum	Aluminum Mass-Conserving	Aluminum Deformation	Aluminum Extrusion	aluminum extrusions 2
aluminum	Aluminum Mass-Conserving	Aluminum Deformation	Aluminum Extrusion	aluminum extrusions 3
aluminum	Aluminum Mass-Conserving	Aluminum Deformation	Aluminum Extrusion	aluminum extrusions 4
aluminum	Aluminum Mass-Conserving	Aluminum Deformation	Aluminum Extrusion	aluminum extrusions 5
copper	Copper Mass-Conserving	Copper Deformation	Copper Wire Drawing	copper wire drawing 1
copper	Copper Mass-Conserving	Copper Deformation	Copper Wire Drawing	copper wire drawing 2
copper	Copper Mass-Conserving	Copper Deformation	Copper Wire Drawing	copper wire drawing 3
copper	Copper Mass-Conserving	Copper Deformation	Copper Wire Drawing	copper wire drawing 4
steel	Steel Mass-Conserving	Steel Deformation	Steel Wire Drawing	steel wire drawing 1
steel	Steel Mass-Conserving	Steel Deformation	Steel Wire Drawing	steel wire drawing 2
steel	Steel Mass-Conserving	Steel Deformation	Steel Wire Drawing	steel wire drawing 3
aluminum	Aluminum Mass-Conserving	Aluminum Deformation	Aluminum Sheet Rolling	aluminum sheet rolling
steel	Steel Mass-Conserving	Steel Deformation	Steel Sheet Rolling	chromium steel sheet rolling
copper	Copper Mass-Conserving	Copper Deformation	Copper Sheet Rolling	copper sheet rolling
steel	Steel Mass-Conserving	Steel Deformation	Steel Sheet Rolling	steel sheet rolling
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray iron casting 1

iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	ductile iron pipe casting 1
steel	Steel Mass-Conserving	Steel Consolidation	steel casting	steel casting 1
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Die Casting	high pressure aluminum die casting
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Sand Casting	aluminum sand casting 1
magnesium	Magnesium Mass-Conserving	Magnesium Consolidation	magnesium die casting	magnesium die casting 1
zinc	Zinc Mass-Conserving	Zinc Consolidation	zinc die casting	zinc die casting 1
copper	Copper Mass-Conserving	Copper Consolidation	copper sand casting	copper sand casting 1
iron	Iron Mass-Conserving	Iron Consolidation	Iron Casting	iron sand casting 1
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	aluminum lost foam casting	aluminum lost foam casting 1
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Sand Casting	aluminum sand casting 2
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	aluminum casting	aluminum casting 1
steel	Steel Mass-Conserving	Steel Consolidation	steel casting	steel casting 2
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 1
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray iron casting 2
steel	Steel Mass-Conserving	Steel Consolidation	steel and iron casting	steel and iron casting
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 2
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 1
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 3
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 2
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray iron casting 2
steel	Steel Mass-Conserving	Steel Consolidation	steel investment casting	steel investment casting 1
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 3
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray iron casting 3
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 4
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 4

steel	Steel Mass-Conserving	Steel Consolidation	steel casting	steel casting 3
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 5
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 5
iron	Iron Mass-Conserving	Iron Consolidation	Iron Casting	iron sand casting 2
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 6
zinc	Zinc Mass-Conserving	Zinc Consolidation	zinc die casting	zinc die casting 2
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 7
iron	Iron Mass-Conserving	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 8
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 6
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 7
aluminum	Aluminum Mass-Conserving	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 8
copper	Copper Mass-Conserving	Copper Consolidation	brass castings	brass castings 1
copper	Copper Mass-Conserving	Copper Consolidation	brass castings	brass castings 2
zinc	Zinc Mass-Conserving	Zinc Consolidation	zinc die casting	zinc die casting 3
titanium	Titanium Mass-Conserving	Titanium Consolidation	titanium casting	titanium castings 1
titanium	Titanium Mass-Conserving	Titanium Consolidation	titanium castings	titanium castings 2
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning steel	Turning steel, conventional, average
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning steel	Turning steel, conventional, primarily roughing
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning steel	Turning steel, conventional, primarily dressing
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning steel	Turning steel, CNC, average
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning steel	Turning steel, CNC, primarily roughing
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning steel	Turning steel, CNC, primarily dressing
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, conventional, average
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, conventional, primarily roughing
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, conventional, primarily dressing

steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, CNC, average
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, CNC, primarily roughing
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, CNC, primarily dressing
iron	Iron Mass-Reducing	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, conventional, average
iron	Iron Mass-Reducing	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, conventional, primarily roughing
iron	Iron Mass-Reducing	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, conventional, primarily dressing
iron	Iron Mass-Reducing	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, CNC, average
iron	Iron Mass-Reducing	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, CNC, primarily roughing
iron	Iron Mass-Reducing	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, CNC, primarily dressing
aluminum	Aluminum Mass-Reducing	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, conventional, average
aluminum	Aluminum Mass-Reducing	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, conventional, primarily roughing
aluminum	Aluminum Mass-Reducing	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, conventional, primarily dressing
aluminum	Aluminum Mass-Reducing	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, CNC, average
aluminum	Aluminum Mass-Reducing	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, CNC, primarily roughing
aluminum	Aluminum Mass-Reducing	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, CNC, primarily dressing
copper	Copper Mass-Reducing	Copper Mechanical Reducing	Turning brass	Turning brass, conventional, average
copper	Copper Mass-Reducing	Copper Mechanical Reducing	Turning brass	Turning brass, conventional, primarily roughing
copper	Copper Mass-Reducing	Copper Mechanical Reducing	Turning brass	Turning brass, conventional, primarily dressing
copper	Copper Mass-Reducing	Copper Mechanical Reducing	Turning brass	Turning brass, CNC, average
copper	Copper Mass-Reducing	Copper Mechanical Reducing	Turning brass	Turning brass, CNC, primarily roughing

copper	Copper Mass-Reducing	Copper Mechanical Reducing	Turning brass	Turning brass, CNC, primarily dressing
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Milling steel	Milling steel, average
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Milling steel	Milling steel, large parts
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Milling steel	Milling steel, small parts
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Milling steel	Milling steel, dressing
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Milling chromium steel	Milling chromium steel, average
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Milling chromium steel	Milling chromium steel, large parts
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Milling chromium steel	Milling chromium steel, small parts
steel	Steel Mass-Reducing	Steel Mechanical Reducing	Milling chromium steel	Milling chromium steel, dressing
iron	Iron Mass-Reducing	Iron Mechanical Reducing	Milling cast iron	Milling cast iron, average
iron	Iron Mass-Reducing	Iron Mechanical Reducing	Milling cast iron	Milling cast iron, large parts
iron	Iron Mass-Reducing	Iron Mechanical Reducing	Milling cast iron	Milling cast iron, small parts
iron	Iron Mass-Reducing	Iron Mechanical Reducing	Milling cast iron	Milling cast iron, dressing
aluminum	Aluminum Mass-Reducing	Aluminum Mechanical Reducing	Milling aluminum	Milling aluminum, average
aluminum	Aluminum Mass-Reducing	Aluminum Mechanical Reducing	Milling aluminum	Milling aluminum, large parts
aluminum	Aluminum Mass-Reducing	Aluminum Mechanical Reducing	Milling aluminum	Milling aluminum, small parts
aluminum	Aluminum Mass-Reducing	Aluminum Mechanical Reducing	Milling aluminum	Milling aluminum, dressing

A.5 Complete Hierarchy of Levels and Processes – Metal Type at L2

L1	L2	L3	L4	L5
Mass-Conserving	MC Steel	Steel Deformation	Steel Forging	carbon and alloy steel forgings
Mass-Conserving	MC Steel	Steel Deformation	Steel Forging	steel forgings 1
Mass-Conserving	MC Steel	Steel Deformation	Steel Forging	steel forgings 2

Mass-Conserving	MC Steel	Steel Deformation	Steel Forging	steel forgings 3
Mass-Conserving	MC Steel	Steel Deformation	Steel Forging	steel forging
Mass-Conserving	MC Steel	Steel Deformation	Steel Forging	steel forgings 4
Mass-Conserving	MC Aluminum	Aluminum Deformation	Aluminum Forging	aluminum forgings
Mass-Conserving	MC Aluminum	Aluminum Deformation	Aluminum Forging	aluminum forgings 2
Mass-Conserving	MC Steel	Steel Deformation	Steel Extrusion	steel extrusion
Mass-Conserving	MC Aluminum	Aluminum Deformation	Aluminum Extrusion	aluminum extrusions
Mass-Conserving	MC Aluminum	Aluminum Deformation	Aluminum Extrusion	aluminum extrusions 2
Mass-Conserving	MC Aluminum	Aluminum Deformation	Aluminum Extrusion	aluminum extrusions 3
Mass-Conserving	MC Aluminum	Aluminum Deformation	Aluminum Extrusion	aluminum extrusions 4
Mass-Conserving	MC Aluminum	Aluminum Deformation	Aluminum Extrusion	aluminum extrusions 5
Mass-Conserving	MC Copper	Copper Deformation	Copper Wire Drawing	copper wire drawing 1
Mass-Conserving	MC Copper	Copper Deformation	Copper Wire Drawing	copper wire drawing 2
Mass-Conserving	MC Copper	Copper Deformation	Copper Wire Drawing	copper wire drawing 3
Mass-Conserving	MC Copper	Copper Deformation	Copper Wire Drawing	copper wire drawing 4
Mass-Conserving	MC Steel	Steel Deformation	Steel Wire Drawing	steel wire drawing 1
Mass-Conserving	MC Steel	Steel Deformation	Steel Wire Drawing	steel wire drawing 2
Mass-Conserving	MC Steel	Steel Deformation	Steel Wire Drawing	steel wire drawing 3
Mass-Conserving	MC Aluminum	Aluminum Deformation	Aluminum Sheet Rolling	aluminum sheet rolling
Mass-Conserving	MC Steel	Steel Deformation	Steel Sheet Rolling	chromium steel sheet rolling
Mass-Conserving	MC Copper	Copper Deformation	Copper Sheet Rolling	copper sheet rolling
Mass-Conserving	MC Steel	Steel Deformation	Steel Sheet Rolling	steel sheet rolling
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray iron casting 1
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	ductile iron pipe casting 1
Mass-Conserving	MC Steel	Steel Consolidation	steel casting	steel casting 1

Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Die Casting	high pressure aluminum die casting
Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Sand Casting	aluminum sand casting 1
Mass-Conserving	MC Magnesium	Magnesium Consolidation	magnesium die casting	magnesium die casting 1
Mass-Conserving	MC Zinc	Zinc Consolidation	zinc die casting	zinc die casting 1
Mass-Conserving	MC Copper	Copper Consolidation	copper sand casting	copper sand casting 1
Mass-Conserving	MC Iron	Iron Consolidation	Iron Casting	iron sand casting 1
Mass-Conserving	MC Aluminum	Aluminum Consolidation	aluminum lost foam casting	aluminum lost foam casting 1
Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Sand Casting	aluminum sand casting 2
Mass-Conserving	MC Aluminum	Aluminum Consolidation	aluminum casting	aluminum casting 1
Mass-Conserving	MC Steel	Steel Consolidation	steel casting	steel casting 2
Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 1
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray iron casting 2
Mass-Conserving	MC Steel	Steel Consolidation	steel and iron casting	steel and iron casting
Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 2
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 1
Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 3
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 2
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray iron casting 2
Mass-Conserving	MC Steel	Steel Consolidation	steel investment casting	steel investment casting 1
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 3
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray iron casting 3
Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 4
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 4
Mass-Conserving	MC Steel	Steel Consolidation	steel casting	steel casting 3
Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 5

Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 5
Mass-Conserving	MC Iron	Iron Consolidation	Iron Casting	iron sand casting 2
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 6
Mass-Conserving	MC Zinc	Zinc Consolidation	zinc die casting	zinc die casting 2
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 7
Mass-Conserving	MC Iron	Iron Consolidation	Gray and Ductile Iron Casting	gray and ductile iron castings 8
Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 6
Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 7
Mass-Conserving	MC Aluminum	Aluminum Consolidation	Aluminum Die Casting	aluminum die castings 8
Mass-Conserving	MC Copper	Copper Consolidation	brass castings	brass castings 1
Mass-Conserving	MC Copper	Copper Consolidation	brass castings	brass castings 2
Mass-Conserving	MC Zinc	Zinc Consolidation	zinc die casting	zinc die casting 3
Mass-Conserving	MC Titanium	Titanium Consolidation	titanium casting	titanium castings 1
Mass-Conserving	MC Titanium	Titanium Consolidation	titanium castings	titanium castings 2
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning steel	Turning steel, conventional, average
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning steel	Turning steel, conventional, primarily roughing
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning steel	Turning steel, conventional, primarily dressing
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning steel	Turning steel, CNC, average
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning steel	Turning steel, CNC, primarily roughing
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning steel	Turning steel, CNC, primarily dressing
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, conventional, average
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, conventional, primarily roughing
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, conventional, primarily dressing

Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, CNC, average
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, CNC, primarily roughing
Mass-Reducing	MR steel	Steel Mechanical Reducing	Turning chromium steel	Turning chromium steel, CNC, primarily dressing
Mass-Reducing	MR iron	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, conventional, average
Mass-Reducing	MR iron	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, conventional, primarily roughing
Mass-Reducing	MR iron	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, conventional, primarily dressing
Mass-Reducing	MR iron	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, CNC, average
Mass-Reducing	MR iron	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, CNC, primarily roughing
Mass-Reducing	MR iron	Iron Mechanical Reducing	Turning cast iron	Turning cast iron, CNC, primarily dressing
Mass-Reducing	MR aluminum	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, conventional, average
Mass-Reducing	MR aluminum	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, conventional, primarily roughing
Mass-Reducing	MR aluminum	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, conventional, primarily dressing
Mass-Reducing	MR aluminum	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, CNC, average
Mass-Reducing	MR aluminum	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, CNC, primarily roughing
Mass-Reducing	MR aluminum	Aluminum Mechanical Reducing	Turning aluminum	Turning aluminum, CNC, primarily dressing
Mass-Reducing	MR brass	Copper Mechanical Reducing	Turning brass	Turning brass, conventional, average
Mass-Reducing	MR brass	Copper Mechanical Reducing	Turning brass	Turning brass, conventional, primarily roughing
Mass-Reducing	MR brass	Copper Mechanical Reducing	Turning brass	Turning brass, conventional, primarily dressing

Mass-Reducing	MR brass	Copper Mechanical Reducing	Turning brass	Turning brass, CNC, average
Mass-Reducing	MR brass	Copper Mechanical Reducing	Turning brass	Turning brass, CNC, primarily roughing
Mass-Reducing	MR brass	Copper Mechanical Reducing	Turning brass	Turning brass, CNC, primarily dressing
Mass-Reducing	MR steel	Steel Mechanical Reducing	Milling steel	Milling steel, average
Mass-Reducing	MR steel	Steel Mechanical Reducing	Milling steel	Milling steel, large parts
Mass-Reducing	MR steel	Steel Mechanical Reducing	Milling steel	Milling steel, small parts
Mass-Reducing	MR steel	Steel Mechanical Reducing	Milling steel	Milling steel, dressing
Mass-Reducing	MR steel	Steel Mechanical Reducing	Milling chromium steel	Milling chromium steel, average
Mass-Reducing	MR steel	Steel Mechanical Reducing	Milling chromium steel	Milling chromium steel, large parts
Mass-Reducing	MR steel	Steel Mechanical Reducing	Milling chromium steel	Milling chromium steel, small parts
Mass-Reducing	MR steel	Steel Mechanical Reducing	Milling chromium steel	Milling chromium steel, dressing
Mass-Reducing	MR iron	Iron Mechanical Reducing	Milling cast iron	Milling cast iron, average
Mass-Reducing	MR iron	Iron Mechanical Reducing	Milling cast iron	Milling cast iron, large parts
Mass-Reducing	MR iron	Iron Mechanical Reducing	Milling cast iron	Milling cast iron, small parts
Mass-Reducing	MR iron	Iron Mechanical Reducing	Milling cast iron	Milling cast iron, dressing
Mass-Reducing	MR aluminum	Aluminum Mechanical Reducing	Milling aluminum	Milling aluminum, average
Mass-Reducing	MR aluminum	Aluminum Mechanical Reducing	Milling aluminum	Milling aluminum, large parts
Mass-Reducing	MR aluminum	Aluminum Mechanical Reducing	Milling aluminum	Milling aluminum, small parts
Mass-Reducing	MR aluminum	Aluminum Mechanical Reducing	Milling aluminum	Milling aluminum, dressing