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Benefits and Risks of Emerging Technologies: Integrating Life Cycle Assessment and Decision Analysis To Assess Lumber Treatment Alternatives

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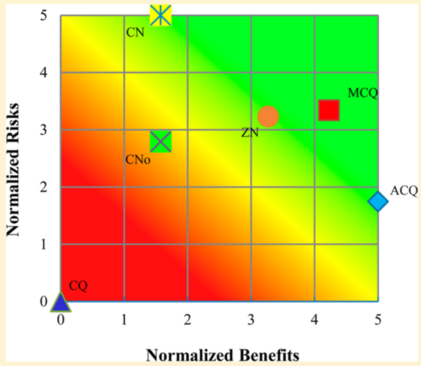
ABSTRACT: Assessing the best options among emerging technologies (e.g., new chemicals, nanotechnologies) is complicated because of trade-offs across benefits and risks that are difficult to quantify given limited and fragmented availability of information. This study demonstrates the integration of multicriteria decision analysis (MCDA) and life cycle assessment (LCA) to address technology alternative selection decisions. As a case study, prioritization of six lumber treatment alternatives [micronized copper quaternary (MCQ); alkaline copper quaternary (ACQ); water-borne copper naphthenate (CN); oil-borne copper naphthenate (CN_o); water-borne copper quinolate (CQ); and water-borne zinc naphthenate (ZN)] for military use are considered. Multiattribute value theory (MAVT) is used to derive risk and benefit scores. Risk scores are calculated using a cradle-to-gate LCA. Benefit scores are calculated by scoring of cost, durability, and corrosiveness criteria. Three weighting schemes are used, representing Environmental, Military and Balanced stakeholder perspectives. Aggregated scores from all three perspectives show CQ to be the least favorable alterative. MCQ is identified as the most favorable alternative from the Environmental stakeholder perspective. From the Military stakeholder perspective, ZN is determined to be the most favorable alternative, followed closely by MCQ. This type of scoring and ranking of multiple heterogeneous criteria in a systematic and transparent way facilitates better justification of technology selection and regulation.



1. INTRODUCTION

Governments and industry often choose between technology options taking into account only a single decision criterion.[1] The U.S. Department of Defense (DOD) is responsible for shipping large amounts of munitions throughout the world. The U.S. Army alone produces 60 000 tons of training munitions each year.[2] These munitions are often shipped around the world in wooden pallets made of treated lumber. Treatment should ensure that materials are stable in harsh environments and do not degrade munitions but should also be cost-effective. The DOD has used zinc naphthenate (ZN)-treated lumber to ship its supplies around the world. This decision was based on a U.S. Department of Agriculture (USDA) study[3] that examined 39 preservative types (including copper- and zinc-based preservatives and pentachlorophenol) tested at two locations in Panama and Mississippi, which demonstrated ZN's efficacy against rot, decay, and corrosion to hardware.[3] However, this approach did not consider the greater environmental footprint of some preservatives across the life cycle of the treatment decision. Since ZN is no longer a registered product with the U.S. Environmental Protection Agency, DOD must now find a suitable replacement. Adding life cycle environmental criteria[1] to material sourcing decisions can strengthen decision making and better represent a broader array of DOD concerns. Simultaneously articulating and applying consistent methods for evaluating these criteria also make the decision more transparent.

Well-informed decisions generally require a great deal of information and data that advise decision-makers what risks and benefits exist among competing alternatives. Many types of risk may be relevant, from financial to environmental and social. Transparent means of weighing and balancing multiple criteria are needed to decrease uncertainty and increase decision strength. Life cycle assessment (LCA) is a method of tracking and quantifying environmental and human health impacts of a product or process. LCA compiles an inventory of inputs and outputs at each stage of the life cycle and then uses this information to calculate potential impacts.[4] LCA is a broad-scope environmental management tool but leaves decision makers with the challenge of appropriately integrating this information into their decisions.

The objectives of this study are to demonstrate the integration of LCA with multicriteria decision analysis (MCDA) to produce a consistent and transparent ranking of technology alternatives. As a proof of concept, this paper scores and ranks the risks and benefits of six lumber treatment alternatives considered by the DOD. The proposed methodology in this study follows the integration of MCDA, LCA, and risk assessment (RA) developed by Linkov and Seager[5] and

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Mitchell et al.[6] The conceptual framework of Linkov and Seager[5] illustrates its application to combine exposure criteria for chemicals based on their physicochemical properties and also life-cycle potentials, producing a dimensionless single score for each chemical. This study is the first to integrate cradle-to-gate product risks with technology benefits involving a nanoenabled product.

2. METHODS

2.1. Technology Alternatives. The following technology options were considered in this study: micronized copper quaternary (MCQ); alkaline copper quaternary (ACQ); water-borne copper naphthenate (CN); oil-borne copper naphthenate (CN_o); water-borne copper quinolate (CQ); and water-borne zinc naphthenate (ZN). The first five products contain copper as the metal biocide, while the sixth uses zinc. Besides MCQ, these products have been used for decades in various applications to protect against decay and pest attacks. ACQ and MCQ are currently the most commonly found treated-lumber products in the residential market. Chromated copper arsenate (CCA) has long been the most common preservative used for outdoor residential applications,[7] until its use was voluntarily restricted in 2003 because of concerns over toxicity. ACQ and MCQ have largely replaced CCA in its prior application areas and are used in a variety of other applications. Naphthenate and quinolate products are generally found in commercial or specialty uses such as utility poles or solutions available for use in individual applications. Preservatives can be applied in either water (water-borne) or oil (oil-borne). Water-borne preservatives such as CN, CQ, and ZN have the advantage of producing lower volatile organic compound emissions.[8] This is important for the health and safety of workers during the production phase. Water-borne preservatives also have the advantage of being cheaper than oil products, which have higher associated costs. Oil-borne preservatives benefit from reduced potential leaching since they are less soluble in water.[8] The smaller amount of leaching may also reduce corrosion since it is the soluble metal cations that instigate galvanic corrosion in lumber.[9] The only oil-borne preservative assessed in this paper, CN_o, is commonly used because of its efficacy and its lower relative mammalian toxicity profile compared with other oil-borne preservatives.[8]

Preservatives can be applied through either dip treatment or pressure treatment. Dip treatment is a simpler method, requiring less infrastructure and energy to treat the lumber. Pressure treatment allows the preservative to penetrate deeper into the lumber. Pressure-treated woods also retain greater amounts of preservatives (Table 1). Both ACQ and MCQ products are pressure-treated. MCQ incorporates nanosized particles of copper salts and is the only product in this study that is treated with a particulate metal solution.[10,11]

Table 1. Lumber Products and Retention Rates

product	retention (lb/ft^3)	treatment type
MCQ	0.34[a]	pressure
ACQ	0.40	pressure
CQ	0.13[b]	dip
CN	0.13[c]	dip
CN_o	0.13[c]	dip
ZN	0.13[c]	dip

[a]International Code Council ESR-1980 standard.[34] [b]AWPA standard UC4A (ground contact, general use).[35] [c]Assumed to be rated at a retention rate similar to that for copper naphthenate (H_2O).

2.2. Decision Framework and Criteria. Following the methods developed by Linkov and Seager[5] and Mitchell et al.,[6] the goal of this study is to prioritize technology options for the aforementioned treated lumber products. Environmental risks and operational benefits are considered as two main decision criteria (Figure 1). The risk score is calculated as an aggregate

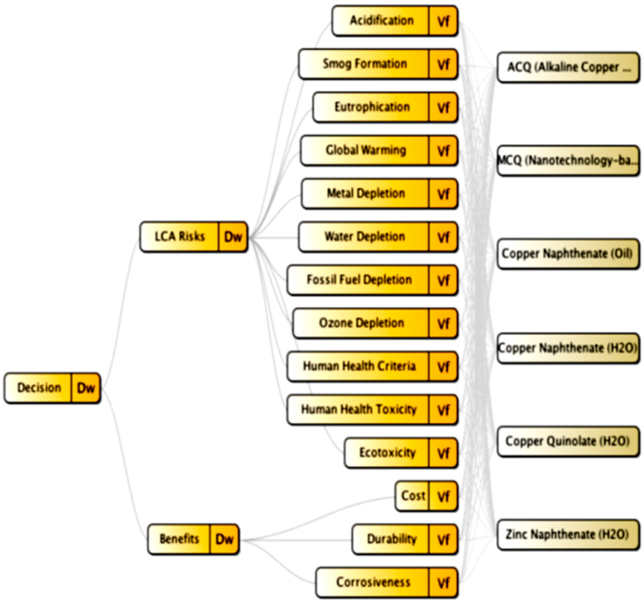

Figure 1. Criteria and metrics evaluated in decision framework.

of 12 individual life cycle impact category scores assessed using an LCA approach.[4] The benefit score aggregates three specific measures related to product use: cost reduction, durability, and corrosiveness. The MCDA approach allows a user to specify the weight associated with each criterion. Representative weights are developed for three stakeholder perspectives: Environmental, Military, and Balanced. Multiattribute value theory (MAVT) is the specific MCDA method used to define weight and score integration. MAVT uses value functions to compare a set of alternative choices for each objective and uses weights to aggregate these into total numerical value scores per alternative. Weights on a 0 to 1 scale sum to 1 and are applied as scaling factors that represent the relative importance of each criterion, with higher values indicating greater importance (Table 3). Here, the weights represent stakeholder preferences independently assessed between risk and benefit criteria, risk subcriteria, and benefit subcriteria. In general, risk aversion was considered a priority for the Environmental perspective (weighting risk higher than benefits); while benefits were considered to be of prime importance for the Military perspective (weighting risks lower than benefits). The way these are applied is described in further detail in a later section. The Balanced stakeholder perspective applies equal weights to all criteria. Although they are based on logical reasons, the weights represent hypothetical scenarios used for proof of concept and were not weights assigned by actual stakeholders during this study.

2.2.1. LCA Risk. Approach. A cradle-to-gate LCA for each product was completed. The LCA tracked material inputs, environmental outputs, and transportation requirements from raw material extraction up through the point of use (Figure 2). Disposal of the lumber was not considered in this LCA because

Table 2. TRACI LCIA Impact Categories with Additional Metal-Specific Impact Categories (Italicized) Used in Our Impact Assessment

impact category	units	description
ozone depletion	kg of CFC-11[a]	converts inventory amounts to CFC-11 equivalents
acidification	H^+	converts inventory amounts to H^+ equivalents
smog formation	kg of O_3	converts inventory amounts to ozone equivalents
eutrophication	kg of nitrogen	converts inventory amounts to nitrogen equivalents
global warming potential	kg of CO_2	converts inventory amounts to CO_2 equivalents
metal depletion	kg of Fe	converts inventory amounts to iron equivalents
water depletion	m^3	ratio of quantity of water used versus water reserves
fossil fuel depletion	kg of oil	ratio of quantity of oil used versus oil reserves
human health criteria	kg of PM_{10}[b]	converts inventory amounts to PM_{10} equivalents
human health toxicity	CTU[c]	converts LD_{50} values to CTU equivalents
ecotoxicity	CTU	converts LC_{50} values to CTU equivalents

[a]CFC-11 = trichlorofluoromethane. [b]PM_{10} = particulate airborne matter less than 10 μm in diameter. [c]CTU = comparative toxicity units.

Table 3. Stakeholder Weights

criterion	Balanced	Military	Environmental
	Benefits		
corrosiveness	0.066	0.208	0.017
cost	0.066	0.523	0.000
durability	0.066	0.208	0.017
	Risks		
acidification	0.066	0.000	0.017
ecotoxicity	0.066	0.000	0.017
energy demand	0.066	0.012	0.400
eutrophication	0.066	0.000	0.017
fossil depletion	0.066	0.012	0.017
global warming	0.066	0.012	0.400
human health criteria	0.066	0.012	0.017
human health toxicity	0.066	0.012	0.017
metal depletion	0.066	0.000	0.017
ozone depletion	0.066	0.000	0.017
smog	0.066	0.012	0.017
water depletion	0.066	0.000	0.017

of a lack of sufficient data on end-of-life behavior of the lumber. The assessment follows the guidance of ISO 14040:2006 and 14044:2006.[4] The functional unit was defined as 1000 m^3 of treated lumber. The environmental impact subcriteria quantified in the study are listed in Table 2.

Life Cycle Inventory. The LCA inventories for the lumber products follow the methodology of Tsang et al.[12] In short, southern yellow pine lumber is the lumber product being treated in each case, with "softwood dimensional lumber" from Ecoinvent 2.0[13] providing the inventory. The active-ingredient retention rates of the lumber products were identified using manufacturers' material safety data sheets and used to calculate the amounts of treatment solution needed per cubic meter of lumber. ACQ and MCQ are produced using a 2:1 ratio of copper to cobiocide [i.e., copper oxide to didecyldimethylammonium carbonate (DDAC)]. Micronization of the copper is performed in a ball mill using a wet grinding method.[12] Copper naphthenate is produced from copper oxide and naphthenic acid, using production of "methylcyclopentane" from Ecoinvent 2.0[13] as a substitution in the absence of specific information on the former. Similarly, zinc naphthenate is produced from zinc oxide and naphthenic acid (via methylcyclopentane). Copper quinolate is produced using copper oxide and quinoline, the latter using the Skraup synthesis method.[12] A combination of secondary data, including available scientific literature[8,14] and patent and industry information,[15−19] was used to derive the exact amounts of material and energy inputs for each product. Basic stoichiometric calculations were made for material syntheses assuming 100% yields and no generated waste. Any energy requirements during solution production were assumed to equal the amount of energy required to heat material inputs to the specified reaction temperatures and were calculated using values of specific heat. ACQ and MCQ are pressure-treated. Energy requirements for pressure treatment were derived from data acquired by Bolin and Smith[14] using a survey of multiple ACQ lumber treatment facilities. The treatment process for the naphthenate and quinolate products is assumed to be a dip process, and the energy required for solution application to the lumber (i.e., the energy needed to submerge and lift lumber to and from the solution tank) is considered minimal and is ignored. Average values of reported leaching rates from the literature were used to calculate the leaching of ionic copper from ACQ and MCQ.[8,20,21] These rates were found to be 14.5% and 3.99%, respectively. An estimated 20% of the copper was leached from each CN product.[22] Worst-case scenarios of 30% were assumed for CQ and ZN using professional judgment in the absence of published data. Transportation requirements were estimated according to methodology similar to that of Tsang et al.,[12] details of which will not be repeated here.

Life Cycle Impact Assessment. The impact categories for life cycle impact assessment (LCIA) and their associated units of measurement are listed in Table 2. These subcriteria were quantified using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) version 2.0,[23] Ecoinvent 2.2,[13] and transport processes developed by the U.S. Environmental Protection Agency.[24] TRACI was used because it is a methodology tailored specifically to U.S. conditions.[23] This methodology produces midpoint impacts, reducing the amount of uncertainty in the impact scores.[25] Individual subcriteria were weighted in this study and combined in the overall score using MAVT algorithms (described in greater detail below). OpenLCA version 1.3.0,[26] an open source software program designed for conducting life cycle assessments, was used in this study. The Ecoinvent 2.0 database and TRACI 2.0 were loaded into OpenLCA prior to running the assessment. The unit processes for production and use of ZN, CN_o, CN, and CQ were created and imported into the software by converting Excel spreadsheets into relevant Ecospold files using the Ecospold Access add-in version 1.9.17.[13]

2.2.2. Benefits. Approach. Empirical data were collected to assess subcriteria benefits using published papers.[8,9,27−29] On the basis of discussions with members of the DOD acquisitions community involved with decisions about treated lumber used in packaging and shipping, the following select group of subcriteria were identified as being of highest interest: durability, corrosion resistance, and cost reduction. While

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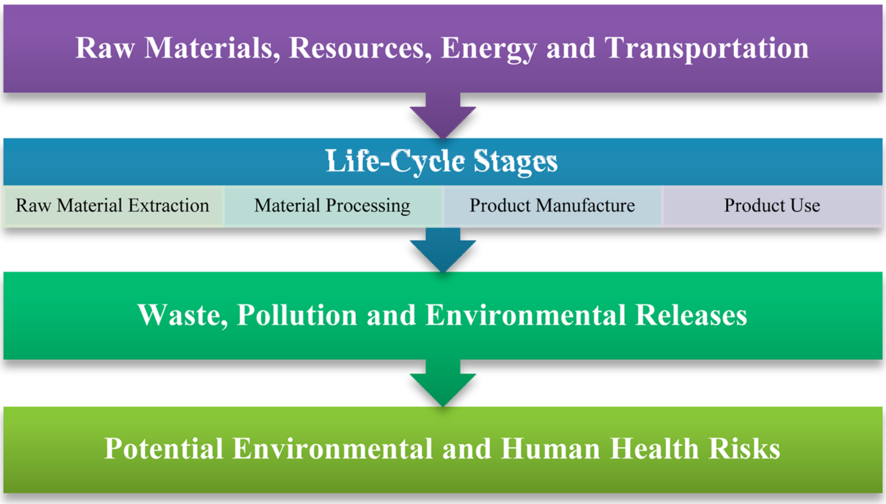

Figure 2. Life cycle stages and corresponding inputs and outputs to the product.

these are not the only subcriteria potentially relevant to the decision, they do represent key concerns from the field and are sufficient to demonstrate the approach. Individual subcriteria are also combined in the overall score using MAVT algorithms (described in greater detail below).

Durability. Durability defines the ability of the treated lumber to withstand decay, rot, and breakdown over time due to pests and environmental factors. Fungal cellar test scores were identified in Stirling et al.[28] for ACQ and MCQ, while those for CN_o were identified in Nicholas and Freeman.[27] From the scientific literature it was not possible to find scores for CN, ZN, and CQ, but on the basis of a qualitative report from the USDA, the performance of these three products can be assumed to be equal to that of CN_o.[3] Values for field stake tests were also used to score durability. Freeman and McIntyre[8] reported values for ACQ and MCQ, Stirling et al.[28] for MCQ, and Nicholas and Freeman[27] for CN_o. Similarly, on the basis of the previously mentioned USDA report, values reported in Nicholas and Freeman[27] for CN_o were used to infer scores for CN, ZN, and CQ. Per the standards inherent to the tests, wood sample scores are rated on a scale of 0−10, where 10 represents complete integrity and 0 represents absolute decay. The values for the fungal cellar scores were averaged together, as were the field stake tests. The averages of those averages were derived to determine final durability scores. Normalization and weighting of scores is explained in greater detail below.

Corrosiveness. Single-point estimates were made for the corrosiveness of each product. Corrosiveness is defined as the degradation rate of the metal hardware—used to nail, screw, or brace the lumber material together—by galvanic corrosion due to the presence of metal ions in the preservatives used to treat the lumber.[9] Corrosiveness is measured in milliinches per year (mpy). Zelinka et al.[29] provided corrosion data for MCQ and ACQ with galvanized steel hardware. On the basis of a review of literature qualitatively describing the other products, ZN was given a value of 1 mpy (nearly noncorrosive), and CN_o, CN, and CQ were assigned a value of 15 mpy, equivalent to mild corrosiveness.[30,31] The corrosiveness of lumber is indexed on a scale of 0−200, where 0 represents undetectable corrosion and 200 unacceptable levels of corrosion (Table 4).[32] Normalization and weighting of scores is explained in greater detail below.

Table 4. Definition of Corrosion Rates

rating[a]	corrosiveness (mpy)
nearly none	<1
minimal	1−5
mild	5−20
moderate	20−50
extreme	50−200
unacceptable	>200

[a]Adapted from Hendrix.[9]

Cost. Single-price-point estimates were made for each product either directly using available prices or indirectly from prices of component materials. The lowest values were used to provide conservative estimates for each product. Prices for MCQ and ACQ were found through a search of the global material sourcing Web site alibaba.com, and their posted unit prices per cubic meter of lumber were used.[33] Prices for the remaining products could not be found for the identified functional unit. These prices were indirectly calculated using the unit price per weight of bulk treatment solution combined with the required mass of solution for treatment. These values were then added to the price of untreated lumber, all of which were found through alibaba.com.[33] The total cost for each product is reported in U.S. dollars (USD) per cubic meter of treated lumber. Normalization and weighting of scores is explained in greater detail below.

2.3. Calculation Algorithms and Visualization. Raw LCIA scores are normalized per category and per product[6] as

$$\mathrm{LCA}_n^x = \frac{\mathrm{LCA}_{raw} - \mathrm{LCA}_{min}}{\mathrm{LCA}_{max} - \mathrm{LCA}_{min}} \quad (1)$$

where LCA_n^x represents the normalized score for each impact category x, LCA_{max} represents the maximum value across each product, and the minimum value LCA_{min} is set to zero. Each normalized score is assigned a corresponding weight w^x (Table 3). These weights and normalized scores are then aggregated to produce an *initial* single LCA risk score per product, defined as

$$\mathrm{LCA}_i^p = \sum_x w^x \mathrm{LCA}_n^x \quad (2)$$

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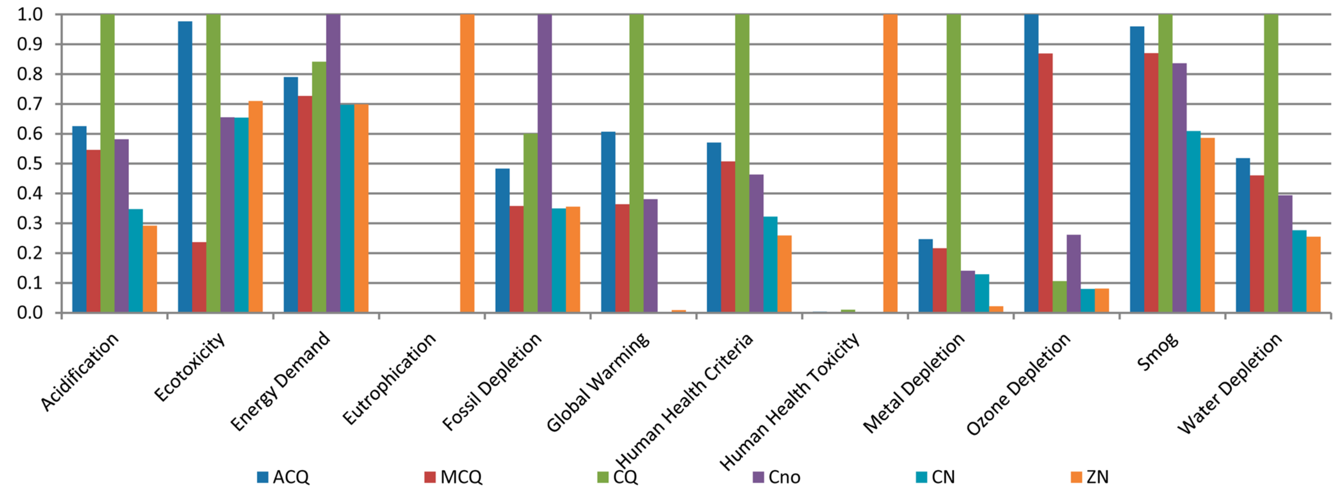

Figure 3. Normalized (unweighted) LCA risks.

where LCA_i^p represents the initial aggregated and weighted LCA value per product p. To facilitate comparison with the benefit scores, where larger scores indicate greater preference, these values are further normalized to produce a *final* single LCA risk score per product:

$$LCA_f^p = \frac{LCA_i^p - LCA_{i,min}^p}{LCA_{i,max}^p - LCA_{i,min}^p} \quad (3)$$

where LCA_f^p is the final single LCA-risk score per product p and the labels min and max represent corresponding values among the six products.

The benefit scores are also normalized, although differently than the LCA scores. The durability scores are averaged together to produce an overall raw score per product. These raw scores are normalized (eq 1) using a minimum value of 0 and maximum of 10, which reflect the scientific consensus for best and worst ratings in these testing categories. Corrosiveness values are normalized (eq 1) using a minimum value of 0 and a maximum of 200, corresponding to published rating boundaries on corrosiveness (Table 4).[9] Costs are normalized (eq 1) using untreated lumber as the minimum price and the price of a wood composite product (a reasonable next-best alternative to treated lumber) as the maximum. Each normalized benefit score is also assigned a corresponding weight (Table 3). Benefit scores and weights are aggregated (eq 2) to produce an *initial* single benefit score per product. These values are then renormalized (eq 3) to produce a *final* single benefit score per product.

A qualitative representation of the final LCA risk and performance benefit criteria scores is produced following the approach of Mitchell et al.[6] Scores are transformed from a scale of 0 to 1 to a scale of 0 to 5, with a score of 5 representing the most favorable outcome, and then reported in a 5 × 5 matrix. The matrix is color-coded in three categories, with green, yellow, and red representing the most favorable, moderate, and least favorable alternative ranges, respectively.

3. RESULTS

3.1. Life Cycle Risks. The unweighted, normalized LCA impact scores are presented in Figure 3. The results show that CN performs most favorably. Although CN has slightly greater impact scores (i.e., lower performance) than ZN in most impact categories, the very high eutrophication and human health toxicity impacts of ZN make CN an overall better alternative. Lumber treated with CQ is evaluated worst. ACQ, ZN, and CN_o perform poorly in various impact categories, but CQ produces the greatest risk for seven of the 12 impacts. The nanoproduct, MCQ, ends up having the second most favorable LCA outcome (i.e., second lowest impact). ACQ has a much greater LCA impact score compared with MCQ despite the fact that the two are fundamentally similar in product formulation. ACQ's larger impact scores are a consequence of its use of monoethanolamine (MEA) as a solvent. Both the upstream production and the transportation of the solvent are factors in the impact results. MCQ and ACQ are applied via pressure treatment, which is more energy-intensive than dip treatment. These two products use only slightly more energy than ZN and CN but less than CQ and CN_o. The two copper naphthenate products have a consistent pattern of impact severity of CN_o > CN. The nature of these two products differs in CN_o's use of a petroleum product as the solvent (Figure 4). The use of these

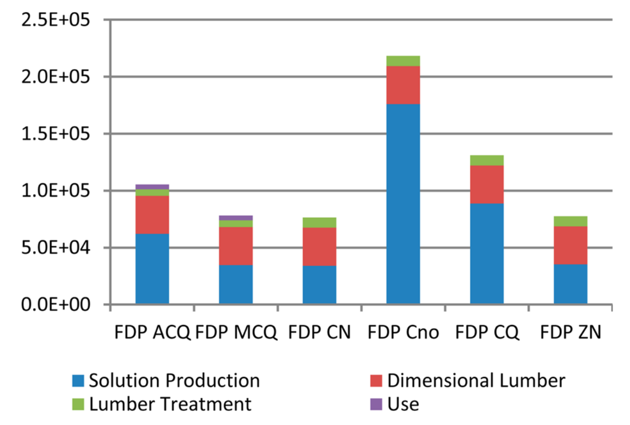

Figure 4. Fossil fuel risk (depletion) per product by life cycle stage.

petroleum products is accompanied by increased upstream impacts during the extraction and processing phase of the production. The third naphthenate product, ZN, has an overall unweighted, normalized score that falls between thosse of the other two naphthenate products. ZN has the most severe impacts in ecotoxicity, human health toxicity, and eutrophication, a consequence of assumed zinc leaching during the use phase.

The final weighting scheme for risks is shown in Table 3. After application of the weights to the normalized LCA scores, the best and worst options are unchanged for each stakeholder (see Table 6). The Environmental stakeholder perspective places greater importance on energy demand and global warming potential. This results in ZN becoming the second-best LCA alternative, while MCQ (the second-best option in the Balanced ranking) becomes the third-best option.

These final scores are relative and should not be confused with absolute values of any given criteria. Because all of the scores are normalized, the values have inherent meaning only when compared with one another and cannot be used to inform decisions outside the context of these alternatives. Because this is a proof of concept study, the data contained in each criterion's data set are not asserted to be exhaustive and conclusive values. Broad estimates, direct values, and assumptions were used in some cases. These uncertainties were not specifically calculated or incorporated into the models.

3.2. Benefits.

Non-normalized benefit scores are listed in Table 5. No product dominated across all criteria, but ACQ had the most favorable total weighted and normalized score for all stakeholder groups. Costs per cubic meter of lumber range from a low of \$264 for ZN to a high of \$472 for CQ. ACQ and MCQ are priced similarly at \$300−333, respectively. ACQ and MCQ have the highest and second-highest corrosion scores at 1.30 and 0.79 mpy, respectively. Although these are the only products whose corrosion values were listed in the scientific literature, the relative similarity of their normalized values reflects the decision context rather than a data bias. On the basis of an assumed corrosion score of 0.04 mpy, ZN is the best-performing product for corrosion. ACQ has the best combined fungal cellar and field stake test score, 9.52 out of 10, making it the best-performing product for durability. MCQ ranks second best with a score of 9.17 out of 10, while the four remaining products are tied for least durable. Consistent with the combined scores, ACQ and MCQ also perform most favorably in the fungal cellar and field stake tests individually.

After application of the stakeholder weights to the benefits data (Table 3), ACQ remains the most favorable option from all three stakeholder perspectives (Table 6). The Military stakeholder perspective places greater importance on the benefits, especially cost, compared to the risks. This results in ZN becoming the second-best benefits alternative, while MCQ (formerly the second-best alternative) becomes the third-best alternative.

3.3. Integration.

The benefit and risk scores are combined in a decision matrix (Figure 5). The weighted and normalized scores that rank in the green zone are considered to be most

Table 5. Unweighted, Non-normalized Benefit Scores for All Six Products

	ACQ	MCQ	CQ	CN_o	CN	ZN
corrosiveness (myp)	1.30	0.79	0.59	0.59	0.59	0.04
cost (USD)	300	333	472	368	368	264
durability (1−10 numerical rank)	9.52	9.17	7.23	7.23	7.23	7.23

Table 6. Risk and Benefit Scores for All Six Products

	ACQ	MCQ	CQ	CN_o	CN	ZN
			Balanced			
benefit: corrosiveness (weighted)	4.29×10^{-4}	2.60×10^{-4}	1.95×10^{-4}	1.95×10^{-4}	1.95×10^{-4}	1.30×10^{-5}
benefit: cost (weighted)	1.25×10^{-2}	1.54×10^{-2}	2.79×10^{-2}	1.86×10^{-2}	1.86×10^{-2}	9.29×10^{-3}
benefit: durability (weighted)	3.19×10^{-3}	5.50×10^{-3}	1.83×10^{-2}	1.83×10^{-2}	1.83×10^{-2}	1.83×10^{-2}
total benefit (renormalized)	0.00	0.17	1.00	0.69	0.69	0.38
total benefit (scaled to 5)	**5.00**	**4.16**	**0.00**	**1.54**	**1.54**	**3.10**
risk (renormalized and weighted)	0.65	0.33	1.00	0.44	0.00	0.35
total risk (scaled to 5)	1.75	3.34	0.00	2.79	5.00	3.23
combined score	6.75	7.50	0.00	4.33	6.54	6.33
rank	2	1	6	5	3	4
			Environmental			
benefit: corrosiveness (weighted)	1.08×10^{-4}	6.57×10^{-5}	4.93×10^{-5}	4.93×10^{-5}	4.93×10^{-5}	3.29×10^{-6}
benefit: cost (weighted)	0	0	0	0	0	0
benefit: durability (weighted)	8.07×10^{-4}	1.39×10^{-3}	4.63×10^{-3}	4.62×10^{-3}	4.63×10^{-3}	4.63×10^{-3}
total benefit (renormalized)	0.00	0.14	1.00	1.00	1.00	0.99
total benefit (scaled to 5)	**5.00**	**4.28**	**0.00**	**0.01**	**0.00**	**0.06**
risk (renormalized and weighted)	0.62	0.34	1.00	0.57	0.00	0.07
total risk (scaled to 5)	1.91	3.29	0.00	2.14	5.00	4.67
combined score	6.91	7.57	0.00	2.15	5.00	4.73
rank	2	1	6	5	3	4
			Military			
benefit: corrosiveness (weighted)	1.35×10^{-3}	8.20×10^{-4}	6.15×10^{-4}	6.15×10^{-4}	6.15×10^{-4}	4.10×10^{-5}
benefit: cost (weighted)	1.25×10^{-2}	1.54×10^{-2}	2.79×10^{-2}	1.86×10^{-2}	1.86×10^{-2}	9.29×10^{-3}
benefit: durability (weighted)	3.19×10^{-3}	5.50×10^{-3}	1.83×10^{-2}	1.83×10^{-2}	1.83×10^{-2}	1.83×10^{-2}
total benefit (renormalized)	0.00	0.18	1.00	0.56	0.56	0.12
total benefit (scaled to 5)	**5.00**	**4.11**	**0.00**	**2.18**	**2.18**	**4.38**
risk (renormalized and weighted)	0.58	0.34	1.00	0.69	0.00	0.38
total risk (scaled to 5)	2.10	3.28	0.00	1.56	5.00	3.12
combined score	7.10	7.39	0.00	3.74	7.18	7.50
rank	4	2	6	5	3	1

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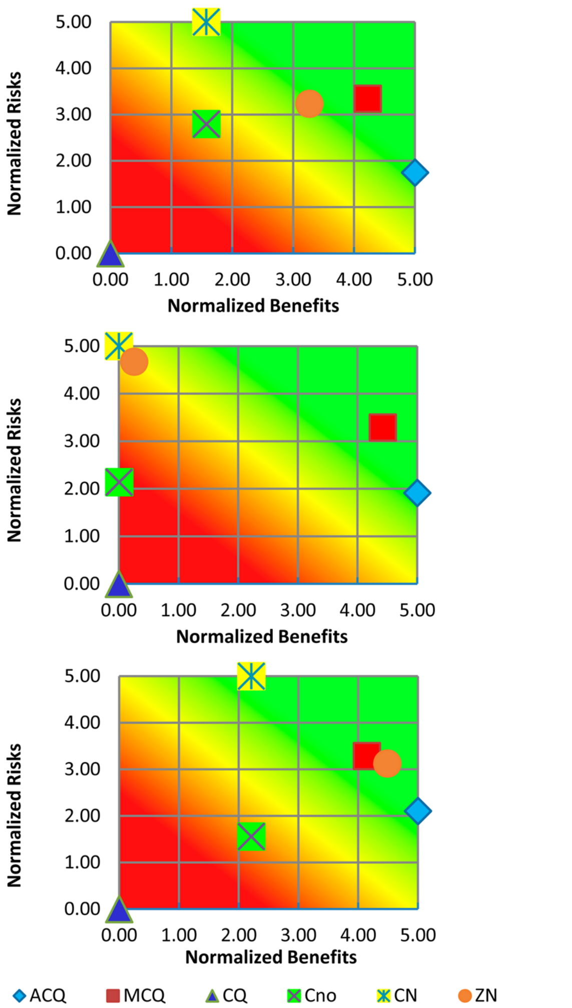

Figure 5. Decision matrix for the (a) Balanced, (b) Environmental, and (c) Military weighting perspectives. Higher values indicate greater preference with respect to both normalized risk and benefit scores. Green, yellow, and red regions represent the most favorable, moderate, and least favorable alternative ranges, respectively.

favorable, those in the yellow zone moderately favorable, and those in the red zone least favorable. The results obtained by combining the risk and benefit scores demonstrate a clear departure from the rankings of either dimension individually. All three stakeholder perspectives evaluate CQ to be the least favorable alterative overall. However, the Military stakeholder perspective determines ZN to be the most favorable alternative, while MCQ is the most favorable alternative for the Environmental stakeholder perspective. ZN is no longer registered with the EPA, but the decision matrix shows that MCQ is a nearly equally favorable alternative and could be an effective substitute. While MCQ is ranked second for the Military stakeholder, the converse is not true from the Environmental perspective, where ACQ is the second most favorable alternative.

4. DISCUSSION

By combining LCA with MCDA, this study provides a transparent and efficient process to rank product alternatives, including those that are nanoenabled. The raw LCA scores indicate that the products with the lowest environmental risks are CN and MCQ, and there was no uniform preference based on benefits scores. When different products are compared across many criteria, there will be many trade-offs relevant to the decision-making process. To produce decisions that are consistent and transparent, these parameters need to be properly assessed, weighted, normalized, and ranked to reflect the values and interests of the decision makers. Similarly, the selection of an appropriate analytic technique to integrate these parameters should be explicitly discussed. MCDA allows various risks, benefits, and other concerns of the decision makers to be considered simultaneously. This study demonstrates an MCDA-based approach for integrating LCA risks and performance benefits that provides flexibility to assess individual risk and benefit components in their appropriate units and to evaluate explicit trade-offs associated with technology selection. By aggregating product component scores into single numerical values, this method provides a straightforward approach for ranking decision alternatives. The use of LCA and MCDA in the selection of emerging technologies can enhance the relative attractiveness of solutions with limited raw material and energy use and with technological benefits, thus leading to more sustainable technology selections. The proposed approach may be especially relevant in selecting technology alternatives in situations of high data uncertainty and variability, as in the case of lumber treatment alternatives discussed in this study.

There are many issues that need to be carefully considered in implementing the proposed integrated LCA/MCDA methodology for technology evaluations. In this paper, the risk factors associated with technology life cycle are directly taken from LCA impact assessments. The differences between traditional risk assessment and the results from an LCA are, however, substantial. Risk is defined as product of hazard, exposure, and effects. LCA provides metrics for hazard and exposure but does not connect them in dose−response models and does not target specific exposure scenarios. LCA can therefore be applied only for comparative assessment of technology alternatives. The comparative nature of LCA provides an approach for dealing with uncertainty that is attracting attention within the LCA and risk assessment communities. Even though many of model parameters may be uncertain, they do not vary between alternatives. Therefore, they are likely to result in similar over- or underestimation of risks for all of the considered alternatives and thus are unlikely to affect the final ranking. Similarly, benefits are calculated over several metrics and integrated with weights defined by the decision makers, which explicitly includes the decision makers' goals, priorities, and objectives as integral components of the combined LCA/MCDA product evaluation.[1,25]

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Notes

This article has been reviewed in accordance with the Agency's peer and administrative review policies and has been approved for publication by the chief of engineers. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use by the U.S. Army Corps of Engineers (USACE). The research described in this

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