Green Chemistry

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On the Use of "Green" Metrics in the Undergraduate Organic Chemistry Lecture and Lab To Assess the Mass Efficiency of Organic Reactions

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In recent years there has been a concerted effort to introduce undergraduate students to "green" chemistry principles *(1–5)* both in the classroom and in the laboratory when they first learn about organic chemistry. The new catch phrases "green chemistry" and "green engineering" are really about reaction optimization with respect to materials and energy usage, waste reduction from all sources, and overall cost minimization. Also included are minimization of toxicity and hazards and maximization of safety practices. When these terms are applied to the performances of individual chemical reactions, chemical processes, and chemical synthesis plans they really deal with the same issues. All of these ideas are implemented routinely by process chemists and chemical engineers in the chemical industry who operate under a code of good laboratory practice (GLP). The fundamental concept for both green chemistry and green engineering is that ongoing efforts to improve reactions are directly connected to the optimization of key parameters that govern their performances. It is obvious that some of these parameters will need to be maximized and others minimized. In this article we describe the complete quantification of reaction mass efficiency (RME), which is solely a mass quantity that needs to be maximized. The success of utilizing concepts of green chemistry rests in their translation into mathematical language that is precise and can be used in general terms. Synthetic organic chemists will find that the present treatment fits this description and, moreover, presents a visual aid that is easy to use and has broad application to any chemical reaction.

The idea that modern day chemists are seriously concerned about environmental issues and are actively doing something to reverse the negative publicity of their legacy piques student interest in the subject and attracts science students from other disciplines to enroll in such courses. At this university, as in several other institutions, a course in industrial and green chemistry is offered to third- and upper-year undergraduate students. However, despite efforts to integrate green chemistry in the mainstream curriculum not all honors B.Sc. programs in chemistry demand that such a course be mandatory for their program. Curiously at this university such a course is required for the bachelor degree in biotechnology but is optional for all chemistry programs. Nevertheless, the minimum prerequisite is an introductory course in organic chemistry at the second-year level. A summary of the course syllabus and topics covered in the course JA has developed over the last five years *(6)* is found in the Supplemental Material.[W]

A key section of the course is the introduction and implementation of so-called "green metrics" analysis to real-world problems, from bench-scale laboratory procedures and syntheses that students perform when they are first exposed to organic chemistry, to industrial-scale processes for the manufacture of important chemicals such as feedstocks, dyestuffs, and pharmaceuticals. A number of references relating to elementary green metrics analyses *(7–9)* and green chemistry laboratory experiments *(10–28)* have appeared in this *Journal.*

Students first derive fundamental relationships that connect key metrics including reaction yield, atom economy (AE) *(29–31),* environmental impact factor (*E*-factor or E_m) *(32–35),* and reaction mass efficiency (RME) based on the law of conservation of mass *(36).* Students learn to read critically literature procedures from research journals and patents, particularly the notation of Markush structures. They then determine the synthetic efficiencies of such procedures under a variety of experimental conditions for specific and generalized reactions, analyze worst-case scenarios to assess minimum AE and maximum *E*-factor values, perform a complete raw material cost (RMC) analysis, and carry out assessments of various recycling options for the optimization of RMEs. All of these exercises empower students to proceed on their own to continue these analyses in other courses and in their own undergraduate research projects whenever they encounter a practical procedure for a chemical reaction or a synthetic plan to some target molecule.

In this article we show the implementation of the general relation given by eq 1 for RME, derived elsewhere *(36–39)* and in the Supplemental Material[W], to sample undergraduate laboratory experiments:

$$\mathrm{RME} = \varepsilon\,\mathrm{AE}\,\frac{1}{\mathrm{SF}}\,\mathrm{MRP} = \varepsilon\,\mathrm{AE}\,\frac{1}{\mathrm{SF}}\left[\frac{1}{1+\dfrac{\varepsilon\,\mathrm{AE}\,(c+s+\omega)}{\mathrm{SF}\,m_{\mathrm{cp}}}}\right] \quad (1)$$

where ε is the reaction yield ($0 < \varepsilon < 1$); AE is atom economy ($0 < \mathrm{AE} < 1$); SF is the stoichiometric factor that takes into account the use of excess reagents (SF = 1 for stoichiometric reactions carried out with no excess reagents; SF > 1, otherwise); MRP is the material recovery parameter that takes into account other materials used in the reaction and post-reaction phases (workup and purification) such as solvents and washings for extractions ($0 < \mathrm{MRP} < 1$); c, s, and ω are the masses of reaction catalyst, reaction solvent, and all other post-reaction materials respectively; and m_{cp} is the mass of the collected tar-

get product. AE is given by the well-known definition

$$\mathrm{AE} = \frac{\nu_\mathrm{p} M_\mathrm{p}}{\sum_{\text{reagents}} \nu_i M_i} \qquad (2)$$

and the SF, by definition, is given by

$$\mathrm{SF} = 1 + \frac{\sum m_\mathrm{er}}{\sum m_\mathrm{sr}} = 1 + \frac{\mathrm{AE} \sum m_\mathrm{er}}{m_\mathrm{tp}} \qquad (3)$$

where ν_P and ν_i are stoichiometric coefficients of target product and reagent i for balanced chemical equation; M_P and M_i are molar masses of target product and reagent i; m_tp, m_sr, and m_er are the masses of target product, stoichiometric reagents, and excess reagents, respectively. For any balanced chemical reaction in which all byproducts are identified, eq 1 may be used to determine RME under a variety of scenarios. Table 1 summarizes reduced expressions for RME depending on whether or not reaction solvents or other post-reaction materials are recovered. When such a material is recovered it does not appear in the MRP factor. Note that the entry in the last row corresponding to the simplest scenario has appeared in all elementary treatments of green metrics for raw material usage. Since this entry corresponds to the basic RME value and is characteristic of the intrinsic performance of a chemical reaction, it is referred to as a kernel metric. Its value is therefore the maximum achievable RME for a given reaction. The most important points to recognize about eq 1 are that (i) RME can be factored into four independent factors each ranging in value between 0 and 1; (ii) each of these factors acts to attenuate RME; and (iii) the MRP factor is the strongest attenuator of RME since solvents normally account for the bulk mass of reaction materials used in a chemical reaction.

The quantities RME and E_m (Sheldon *E*-factor based on mass) are related by a simple expression given by eq 4, which allows easy calculation of either parameter once one of them is known. It is often simpler to determine E_m first and then to use eq 4 to calculate RME. The derivation of eq 4 is linked to that of eq 1 and is given in the Supplemental Material.[W]

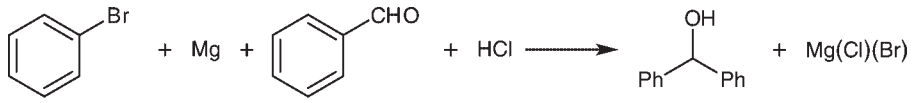
$$\mathrm{RME} = \frac{1}{1 + E_m} \qquad (4)$$

A Microsoft Excel (version 5.0 or higher) spreadsheet template form has been developed that allows students to calculate the complete RME according to eq 1 and raw material cost (RMC) for any chemical transformation they may carry out in the laboratory. Lines are numbered and line instructions are embedded in the same manner as a personal income tax form. Students learn to employ green metrics to evaluate the "greenness" of their experiment in a rigorous quantitative way and to determine the "bottom line" cost of carrying out the experiment. Students are also able to assess improvements to their experiment under various reclaiming and (or) recycling options with respect to materials usage and cost savings. Some of the information can be completed as a prelab exercise such as calculating the molar mass of reagents, finding the densities of liquids (g/mL) from handbooks, and finding the costs of materials used on a per gram basis from a chemical catalogue such as the Aldrich Chemical Catalogue. Formula entries are inserted in appropriate cells to facilitate computation. Students can verify these by performing hand calculations. Any changes made in any input data cell for materials used or cost per gram result in automatic updates of formula entry cells and in the final graphical output. This powerful feature of Excel facilitates analysis of effects of changing any input parameters. The Supplemental Material[W] contains sample results for undergraduate organic chemistry experiments in Excel format along with a template file that can be readily adapted to any chemical transformation.

The five parameters in eq 1 (RME, AE, ε, 1/SF, and MRP) are displayed graphically in the form of a radial pentagon depicting a "materials usage footprint" so that students can recognize at once which of the four factors on the right-hand side of eq 1 are contributing to an attenuation of RME. Each axis corresponding to one of the five parameters emanates from the center and ranges in value between zero and one. The values of these parameters are depicted as dots and these are connected to form a pentagonal figure. The ideal

Table 1. Expressions for RME for Any Chemical Reaction under Various Scenarios

RME Expression	Conditions
$\varepsilon\,\mathrm{AE}\,\frac{1}{\mathrm{SF}}\left[\frac{1}{1 + \frac{\varepsilon\,\mathrm{AE}(c + s + \omega)}{\mathrm{SF}\,m_\mathrm{cp}}}\right]$	excess reagents used; reaction catalyst destined for waste; reaction solvent destined for waste; work-up and purification materials destined for waste
$\varepsilon\,\mathrm{AE}\left[\frac{1}{1 + \frac{\varepsilon\,\mathrm{AE}(c + s + \omega)}{m_\mathrm{cp}}}\right]$	no excess reagents used; reaction catalyst destined for waste; reaction solvent destined for waste; work-up and purification materials destined for waste
$\varepsilon\,\mathrm{AE}\left[\frac{1}{1 + \frac{\varepsilon\,\mathrm{AE}(c + \omega)}{m_\mathrm{cp}}}\right]$	no excess reagents used; reaction catalyst destined for waste; reaction solvent recovered; work-up and purification materials destined for waste
$\varepsilon\,\mathrm{AE}\left[\frac{1}{1 + \frac{\varepsilon\,\mathrm{AE}\,c}{m_\mathrm{cp}}}\right]$	no excess reagents used; reaction catalyst destined for waste; reaction solvent recovered; work-up and purification materials recovered
$\varepsilon\,\mathrm{AE}\,\frac{1}{\mathrm{SF}}$	excess reagents used; reaction catalyst recovered; reaction solvent recovered; work-up and purification materials recovered
$\varepsilon\,\mathrm{AE}$	no excess reagents used; reaction catalyst recovered; reaction solvent recovered; work-up and purification materials recovered



Scheme I. Procedure for the synthesis of diphenylmethanol using the Grignard methodology.

"green" situation is depicted by a regular pentagon of unit radius where each parameter is equal to one. The less "green" a reaction is, the more the resultant pentagon is distorted toward the center. These diagrams may therefore be used to compare the RME performances of different classes of reactions so that students can ascertain which reaction classes are inherently "green" and which are not by visual inspection. The degree of distortion of the radial pentagon from its regular ideal shape may be directly linked to which parameters are responsible for that distortion. These diagrams therefore inform the student as to what to do if they wish to "green up" their experimental procedure, whether it is to reduce reaction solvent usage, cut down on unnecessary washes and extractions, avoid using excess reagents unless there is a chemical reason for doing so as in driving equilibria toward product, select lower-mass reagents to effect improved AE performance, or optimize reaction yield by tweaking with such parameters as reaction time, reaction temperature, reaction pressure, or the use of catalysts.

Students begin by writing fully balanced chemical equations for the transformation they will be performing in the laboratory. Quantities of all chemicals used in the reaction and their associated costs are entered directly in the appropriate cells. Volume measures in milliliters are entered for liquids and mass quantities in grams are entered for any solid materials used. The template form is divided into three parts: raw materials usage (Part 1), green metrics analysis (Part 2), and assessment criteria (Part 3).

The raw materials usage section in Part 1 is in turn divided into three subsections: (A) reaction stage, including reagents, catalysts, and reaction solvents; (B) workup stage; and (C) purification stage. The total mass and total cost of input materials used are determined. From the mass of product collected the cost of product in \$/g (total input materials cost/mass of product collected) is determined. In Part 2, the kernel green metrics atom economy (AE) and environmental impact factor based on molar mass (E_{mm}) are first evaluated. Mass of waste, RME, environmental impact factor based on mass (E_m), and wasted input costs are evaluated under three scenarios: (a) reclaiming reaction solvents, catalysts, byproducts, and all post-reaction materials; (b) committing all reaction solvents, catalysts, byproducts, and all post-reaction materials to waste; and (c) partial reclaiming of materials as appropriate. In Part 3, students make an overall assessment of the experimental procedure according to the following criteria in tabular format: (i) potential for side reactions, (ii) potential for separation of multiple products, (iii) potential for recyclability of byproducts back to reagents, (iv) potential or actual use of a "green" technology, (v) toxicity concerns for reagents, (vi) toxicity concerns for byproducts, (vii) toxicity concerns for solvents, (viii) hazard concerns for reagents, (ix) hazard concerns for byproducts, (x) hazard concerns for solvents, and (xi) energy demands outside of standard temperature pressure conditions of 25 °C and 1 atm.

Sample Laboratory Procedure and Analysis

The following undergraduate laboratory procedure for the synthesis of diphenylmethanol using the Grignard methodology according to Scheme I is given as an illustrative example where the present analysis is employed. To a 25-mL round-bottomed flask charged with 0.4 g dry magnesium turnings is added dropwise a solution of 1.8 mL of bromobenzene in 9 mL of dry ether over 20 minutes. The reaction solution is gently refluxed for a further 20 minutes. A second solution of 1.5 mL of benzaldehyde in 4 mL of dry ether is added dropwise over a period of 20 minutes. After addition is complete the mixture is refluxed for 15 minutes then cooled. The reaction mixture is then poured over 10 g of crushed ice followed by addition of 3 mL of 5% aqueous HCl solution. The ether layer is separated and washed successively with water (30 mL), saturated sodium bisulfite ($NaHSO_3$) solution (30 mL), and again with water (30 mL). After drying with 5 g $MgSO_4$, filtration, and evaporation of the solvent, the crude product is recrystallized from petroleum ether (100 mL) to afford 2.18 g of pure diphenylmethanol. [Note the costs from 2004–2005 Aldrich Chemical Catalogue (\$CAD): Mg turnings (\$170.90/2.5 kg), bromobenzene (\$543.45/18 L), benzaldehyde (\$269/18 kg), 37% HCl (\$125.60/10 L), diethyl ether (\$325/16 L), sodium bisulfite (\$416.50/12 kg), petroleum ether (\$247/12 L), magnesium sulfate (\$618.80/10 kg). No cost is assigned to water.]

Figures 1 and 2 show the results of Parts 1 and 2 for the reaction metrics form in Excel format for this procedure where eq 1 is used to check the overall RME for production of diphenylmethanol according to all materials used. Under conditions of using excess reagents (benzaldehyde is the limiting reagent), the kernel RME for production of diphenylmethanol is 28.2% with a reaction yield of 80%. The cost of producing 2.18 g of this material amounts to \$2.45 or about \$1.12/g. It is clear that the raw material cost on a per gram basis is inversely related to the reaction yield. Since customarily students do not recover reaction solvents and all other post-reaction washings and solvents used in the procedure, the analysis reveals that the overall RME for production of the target product decreases dramatically to 1.1%. In terms of input costs of all materials, this translates into \$2.42 of the \$2.45 spent, or 99%, as destined for waste. If diethyl ether and petroleum ether are recovered at appropriate stages in the synthesis without mixing them with other waste materials and with no added input materials, then \$0.93 of the \$2.45 spent, or 38%, is destined for waste though the overall RME nearly doubles to 1.8%. These kinds of results affect students in a dramatic fashion to the point that they better appreciate the cost of educating themselves in the lab component of an introductory organic chemistry course. The corresponding resultant radial pentagon is shown in Figure 3, along with other scenarios. From this visual representation it is clear that the low overall RME in "no reclaiming"

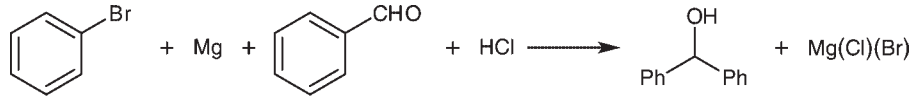
REACTION METRICS FORM

DATE: 21-May-05

NAME OF TARGET PRODUCT: Diphenylmethanol

REACTION CLASSIFICATION: Carbon–carbon bond formation

BALANCED CHEMICAL EQUATIONS:



PART 1: RAW MATERIALS USAGE

(A) REACTION STAGE:

(i) REAGENTS	MW (g/mol)	Density (g/mL)	Volume (mL)	Moles	Mass (g)	Cost ($/g)	Cost ($)	
Mg	24.3			0.0165	0.4	0.0684	0.027	12
Ph-Br	156.9	1.495	1.8	0.0172	2.691	0.0202	0.054	13
Ph-CHO	106	1.046	1.5	0.0148	1.569	0.0149	0.023	14
5% HCl (aq)	36.45	1.02	3	0.084	3.06	0.0014	0.004	15
TOTAL REAGENTS	323.65			Add lines 12 to 15	7.72		0.11	16
(ii) CATALYSTS	MW (g/mol)	Density (g/mL)	Volume (mL)	Moles	Mass (g)	Cost ($/g)	Cost ($)	
None	0	0	0	0	0	0	0.000	19
							0.000	20
TOTAL CATALYSTS				Add lines 19 to 20	0		0.000	21

(iii) SOLVENTS	Density (g/mL)	Volume (mL)		Mass (g)	Cost ($/g)	Cost ($)		
Et_2O	0.708	13		9.204	0.0287	0.264	24	
H_2O	1			10	0	0.000	25	
TOTAL SOLVENTS			Add lines 24 to 25	19.204		0.264	26	
Reaction Materials Subtotals			Add lines 16, 21, 26	26.924		0.374	29	

(B) WORK-UP STAGE:

MATERIAL	Density (g/mL)	Volume (mL)		Mass (g)	Cost ($/g)	Cost ($)		
H_2O	1	60		60	0	0.000	33	
sat $NaHSO_3$ (aq)	1.345	30		40.35	0.0347	0.532	34	
						0.000	35	
						0.000	36	
TOTAL WORK-UP MATERIALS			Add lines 33 to 36	100.35		0.532	37	

(C) PURIFICATION STAGE:

MATERIAL	Density (g/mL)	Volume (mL)		Mass (g)	Cost ($/g)	Cost ($)		
petroleum Et_2O	0.64	100		64	0.0193	1.235	41	
$MgSO_4$				5	0.0619	0.309	42	
						0.000	43	
						0.000	44	
TOTAL PURIFICATION MATERIALS			Add lines 41 to 44	69		1.544	45	
Post-reaction Materials Subtotals			Add lines 37, 45	169.35		2.077	47	
				Mass (g)	Cost ($)			
TOTAL INPUT MATERIALS			Add lines 29, 47	196.274	2.450	50		
	MW (g/mol)	Moles	Yield	Mass (g)	Cost ($/g)			
OUTPUT TARGET PRODUCT	184	0.0118	0.8004	2.18	1.124	53		

Figure 1. The results of Part 1 for the reaction metrics form in Excel format for synthesis of diphenylmethanol.

PART 2: GREEN METRICS ANALYSIS								
Limiting reagent:	Ph-CHO							
PARAMETER	VALUE							
Reaction Scale	0.0148	moles		58				
E(mw)	0.759	MW byproducts/		59				
		MW product						
AE	0.569	MW product/		60				
		S MW reagents						
(i) Under reclaiming reaction solvents, catalysts, and byproducts, and all post-reaction materials								
Mass of waste	5.54	g		63				
(line 16 - 53)								
E(m)	2.541	g waste/g product		64				
RME	0.282	g product/S g reagents		65				
SF	1.611			66				
Wasted input costs ($)	0.079							
(ii) Under committing all reaction solvents, catalysts, and byproducts, and post-reaction materials to waste								
Mass of waste	194.094	g		69				
(line 50 - 53)								
E(m)	89.034	g waste/g product		70				
RME	0.011	g product/S g reagents		71				
Wasted input costs ($)	2.423							
Check formula	0.011							
(iii) Under reclaiming ether from reaction and petroleum ether from purification								
Mass of waste	120.89	g		76				
E(m)	55.454	g waste/g product		77				
RME	0.018	g product/S g reagents		78				
Wasted input costs ($)	0.934							

Figure 2. The results of Part 2 for the reaction metrics form in Excel format for synthesis of diphenylmethanol.

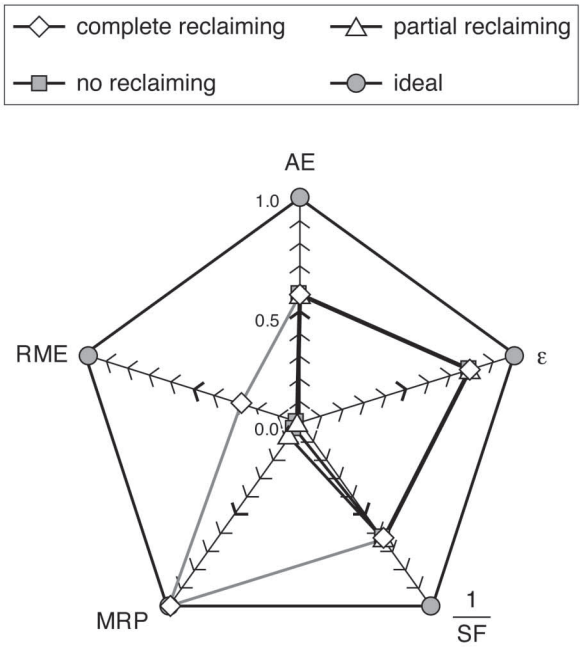


Figure 3. Radial pentagon representing RME values for the synthesis of diphenylmethanol using the Grignard methodology under various scenarios.

scenario is due to a modest AE of 60%, the use of 61% excess reagents, and a minimum MRP of about 4%. The best RME possible for synthesizing diphenylmethanol by this procedure is 28.2 % for the "complete reclaiming" scenario.

Extension to Other Reaction Types

These kinds of analyses have been applied to other reactions carried out in the second- and third-year undergraduate organic laboratory at this university (see Supplemental Material[W]). Table 2 summarizes green metrics analyses and costs for producing target products according to various reaction types. (Corresponding radial pentagons are shown in the Supplemental Material.[W]) The data reveal that over all experiments conducted in a year's laboratory course each student produces 1.6 kg of waste to produce 61 g of target products at a total cost of about $36 for all input materials. The "overall" *E*-factor based on mass is then about 26 kg waste/kg target product. If we assume that this is typical of an undergraduate student at a Canadian university on an annual basis we may estimate the corresponding figures for all undergraduate students taking a lab course in organic chemistry in a typical year at all Canadian universities. Hence, if each of the 60 universities enrolls an average of 300 students per lab course per year then 28,800 kg and 1098 kg of waste

Table 2. Summary of Green Metrics Analyses for Various Reaction Types Shown in Scheme II

Reaction Type	AE	ε	Range of RME	Range of E_m	Product Collected/g	Maximum Waste/g	RMC ($/g Product Collected)
Aldol condensation	0.92	0.80	0.077–0.701	0.43–12.07	4	48.3	0.28
Bromination of an olefin	1	0.68	0.078–0.620	0.61–11.87	0.6	7.1	0.78
Diels–Alder reaction	1	0.85	0.204–0.593	0.69–3.90	5	19.5	0.14
Dehydration of an alcohol	0.82	0.70	0.184–0.575	0.74–4.43	6	26.6	0.07
Debromination of an alkyl halide	0.26	0.80	0.017–0.098	9.16–58.7	6.6	387.7	1.39
Friedel–Crafts alkylation	0.72	0.75	0.117–0.549	0.82–7.58	8	60.6	0.20
Michael 1,4-addition	1	0.76	0.056–0.710	0.41–16.73	0.5	8.4	1.07
Aromatic nitration	0.91	0.70	0.15–0.345	1.90–5.66	5	28.3	1.26
Oxidation of secondary alcohol	0.30	0.58	0.016–0.052	36.67–60.23	2	120.47	1.22
Oximation	0.78	0.87	0.037–0.588	0.70–25.86	5	129.3	0.39
Beckmann rearrangement	1	0.60	0.005–0.600	0.67–220.17	3	660.5	2.62
Bromination of primary alcohol	0.606	0.73	0.123–0.256	2.91–7.14	15	107.07	0.20

Note: Scheme II can be found in the Supplemental Material.

Table 3. Summary of Atom Economical Efficiency Trends for Various Reaction Classifications

Reaction Classification	General Trends
Multi-component reactions	• Most highly atom economical reaction type of all
Carbon–carbon bond forming reactions	• Atom economy increases as the molecular weights of the combining fragments increase
Non-carbon-carbon bond forming reactions	• Atom economy increases as the molecular weights of the combining fragments increase
Condensations	• Highly atom economical since small molecules of water or alcohol are liberated • Atom economy increases as the molecular weights of the combining fragments increase • For cyclization reactions such as the Dieckmann condensation and the synthesis of cyclic ethers from straight chain diols the atom economy increases with increasing ring size
Oxidations or reductions with respect to substrate	• Worst atom economical performance of all (exceptions are catalytic hydrogenation and oxidation with molecular oxygen or hydrogen peroxide) • Characterized by the production of significant waste byproducts that are the result of oxidation or reduction of reducing and oxidizing reagents, respectively • Recycling of byproducts back to the original oxidizing or reducing reagents necessarily involves at least another redox couple
Rearrangements	• Rearrangements of substrates always have atom economies of 100% • Some rearrangement reactions involve rearrangements of intermediates along their reaction pathways and so their corresponding atom economies are less than 100%
Substitutions	• Atom economy increases if the in-coming group is heavier than the leaving group, otherwise it will decrease • The caveat is that good leaving groups tend to be large
Fragmentations/eliminations	• Proportion of high atom economical reactions is low since these reactions are the reverse of skeletal building up reactions • Atom economy decreases as the molecular weight of the leaving fragment increase

and target products are produced, respectively, at a total cost of $648,000 for all input materials. In practice both the waste produced by students and their collected target products are destined for disposal since products are not saved or archived so the real total annual mass of waste is 29,898 kg. A nice way of helping students to visualize such a quantity is to determine how many railway car loads this represents. Typically, a railway tank car can accommodate 100 tons or 90,718 kg of material so about one third of a load of waste is produced per year for all university students in Canada taking an organic lab course.

When the material efficiencies of organic reactions are analyzed according to their classification type, students can explore and discover important general trends that are useful in planning material efficient total syntheses of target molecules. The main classifications of organic reactions are: multicomponent reactions (reactions involving at least three substrates that are brought together sequentially in a specified order or at once in a reaction vessel), carbon–carbon bond forming reactions including additions, couplings, and cyclizations, non-carbon–carbon bond forming reactions, condensations, oxidations with respect to substrate, reductions with respect to substrate, rearrangements, substitutions, and fragmentations, and eliminations. The range of reactions shown in the Supplemental Material[W] covers a fair number of these reaction types. Table 3 summarizes key atom economical trends that can be correlated directly with the shapes of the radial pentagons shown in Figure 4 in the Supplemental

Material.[W] One can see for example that the E2 reaction to produce acetylenedicarboxylic acid and the oxidation of cyclohexanol to cyclohexanone by the Jones procedure are by far the worst performers. In both cases this is because of low atom economies, low MRP values due to the use of excessive solvents and washings for extractions, and the use of excess reagents, though the former reaction exhibits a good reaction yield. The Beckmann rearrangement material performance is poor mainly because of excessive washings used in the workup and purification steps though it has a 100% atom economy. The aldol condensation, olefin bromination, Diels–Alder, Michael 1,4-addition, and aromatic nitration reactions are all good atom economical transformations. The low values for MRP in all reactions severely reduce the overall RME for each reaction.

Summary

A general analysis of reaction mass efficiency and raw material cost has been developed using an Excel spreadsheet format that can be applied to any chemical transformation. Reaction mass efficiency is a quantity that can be factored into four independent factors: reaction yield, atom economy, inverse of stoichiometric factor accounting for the use of excess reagents, and materials recovery parameter accounting for the use of reaction solvents, catalysts, and other materials used in post-reaction operations such as workup and purification procedures. Results are depicted in the style of a tax form and as a radial pentagon that allow the easy visual inspection of which variables contribute to the attenuation of reaction mass efficiency for a given reaction. The effect of various recovery scenarios may also be analyzed. These new methods may be easily incorporated into standard laboratory exercises and lab report write-ups in undergraduate organic labs to assess the "greenness" of student experiments.

[W]Supplemental Material

Derivations of eq 1 and eq 4; course syllabus; Scheme 2; Figure 4; sample results for undergraduate organic chemistry experiments in Excel format along with a template file that can be readily adapted to any chemical transformation; cell definitions; example green metrics forms for several reactions in Microsoft Excel (version 5.0 or higher) format are available in this issue of *JCE Online*.

Acknowledgments

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