TOWARDS A BETTER UNDERSTANDING OF STIRRED MILLING TECHNOLOGIES

ESTIMATING POWER CONSUMPTION AND ENERGY USE

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CMP January 2014

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Peter Radziszewski, ing., PhD, VP Solutions Offering Development,
Research and Technology Development

Peter ('83, BASc Mech Eng, UBC; '86, MSc génie méc., ULaval; '92, PhD génie méc., ULaval) is based in Metso's Lachine offices, but assumes a global role in the conception, facilitation, management and execution of technology strategies and larger or more complex RTD projects and programs, especially those involving co-creation and/or external research contracts. Previously to joining Metso in 2013, Peter Radziszewski has worked in academia specifically in the Abitibi (Professor, UQAT, 1991-2000), Australia (Visiting Scholar, JKMRC, 1997-98), Montreal (Associate Professor, McGill, Mechanical Engineering, since 2001) and the Canadian Space Agency (Visiting Professor, 2007-08). He is the author/co-author of over 100 paper and conference proceedings, one book, four book chapters, 3 patents (wear sensor, instrumented ball, microwave assisted drill) and 1 patent pending (particulate filled metal fabric wheel).

Jonathan Allen, Manager, Stirred Milling Products

Jonathan Allen is the Global product manager for Stirred Mills, including the Stirred Media Detritor (SMD) and the Vertimill®, He is based in York Pennsylvania, USA. Jon holds a Bachelor of Science degree in Mechanical Engineering from the Pennsylvania State University. He joined Metso in 2005 as a product engineer providing technical and commercial support for large SAG and Ball mill grinding projects. His current responsibilities as product liner manager include R&D, product and application support He is deeply involved with all with the management of all disciplines related to product's life cycle.

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Context

"Any sufficiently advanced technology is indistinguishable from magic"

Arthur C Clark

Jon and Peter share a common interest: Space.

Peter is a fan of Star Trek while Jon is a fan of Arthur C Clark.

As a result, they felt it appropriate, in the context of this paper, to start with a quote.

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Context

CMP 2013 Stirred Mill Round Table

Tumbling mills are continuing to be used
in fine and ultrafine grinding applications
despite that in certain circumstances
stirred milling is significantly more efficient than ball milling.

Main Reason: low comfort level with stirred milling technology understanding

At the CMP 2013 round table, a number of questions were asked of the panel by the Moderator (Donald Leroux) which stimulated a lot of debate between the audience present and the panelists. One of the first questions raised and one that stimulated a lot of discussion was related to the observation that despite the reported increased efficiencies in fine grinding of stirred mill technologies, tumbling mills were still being used for re-grind applications.

The general consensus of the people present was that the comfort level in understanding stirred milling technologies is not at the level of that of tumbling mills.

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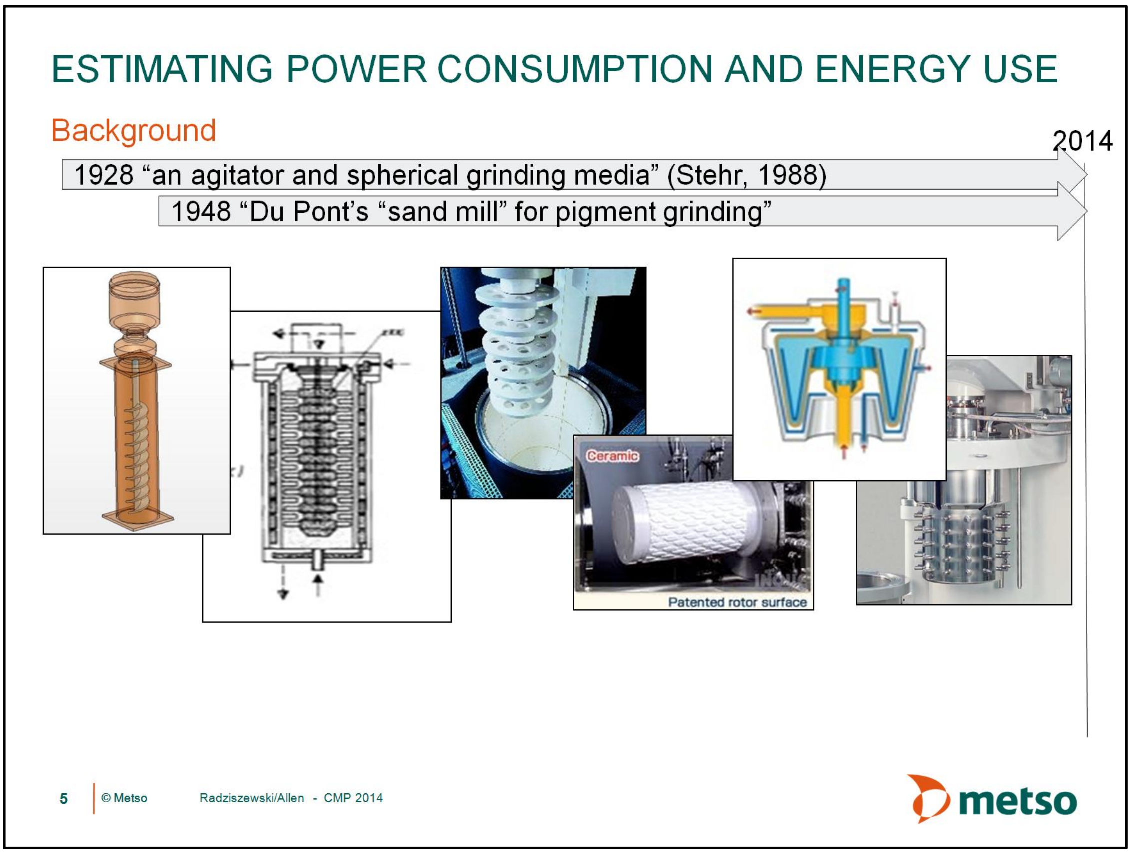
Objective

To contribute to increasing the general comfort level with stirred milling technologies by developing a better understanding of how power and energy is affected by stirred mill impellor design and mill operation.

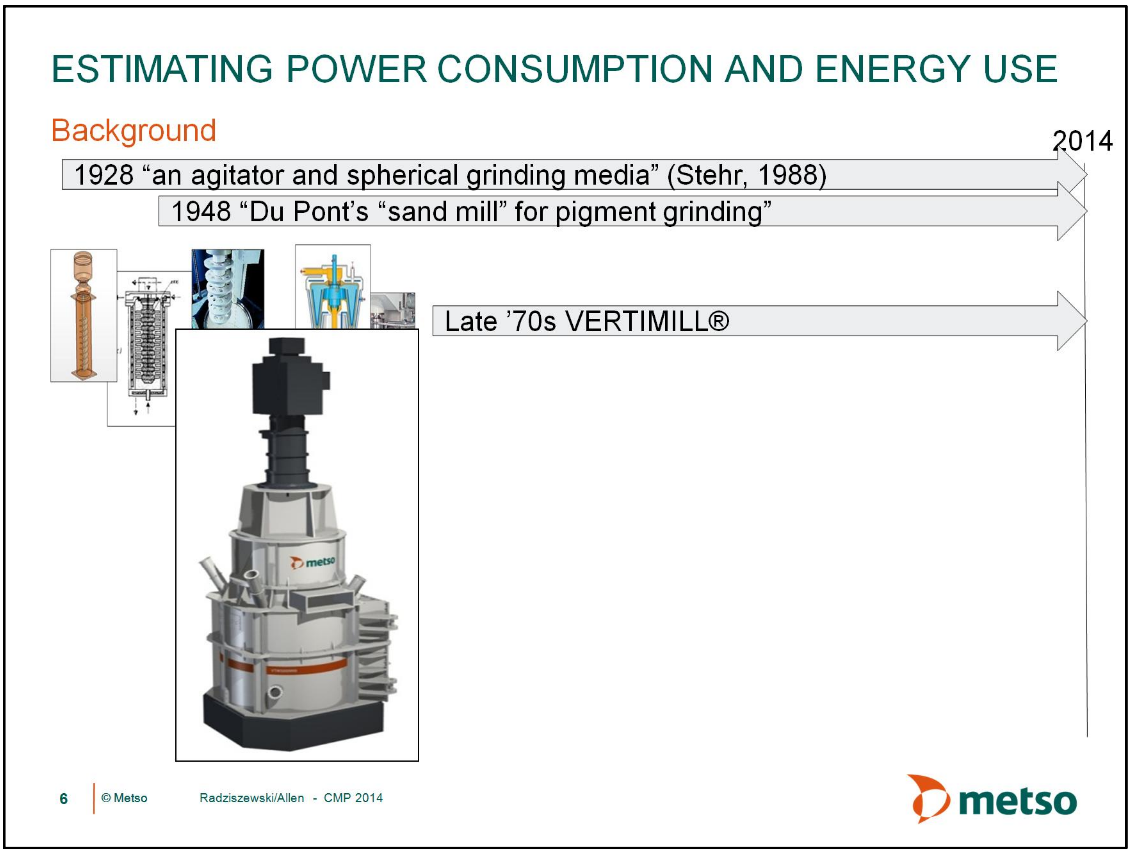
As a result, the aim of this paper is to contribute to increasing the general comfort level with stirred milling technologies.

This will be accomplished by exploring how model power is affected by stirred mill impellor design and mill operation starting with completing first an overview of the power models found in the literature followed by a general description of DEM and CFD stirred mill models as well as the insights that can be drawn from them.

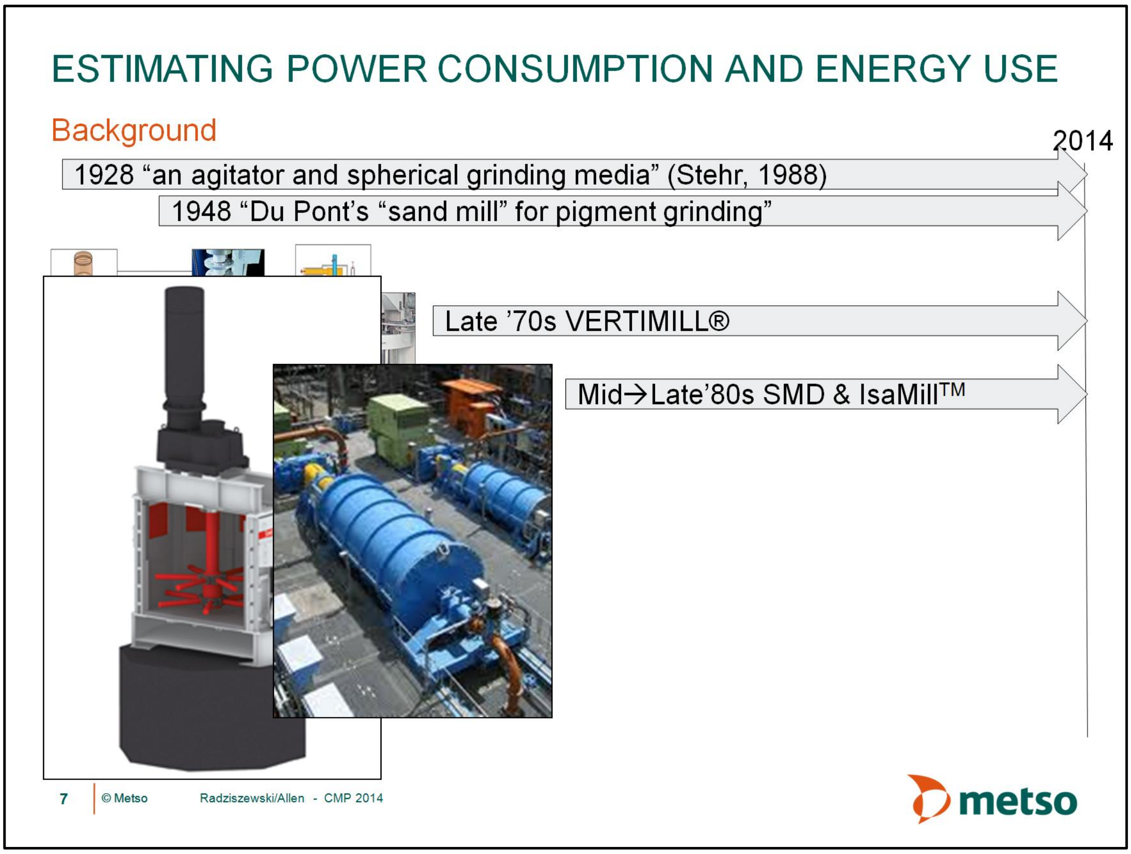
Finally, a generic stirred mill power model will be presented and applied to different stirred mill types in order to develop some insights into the differences between different mill types.



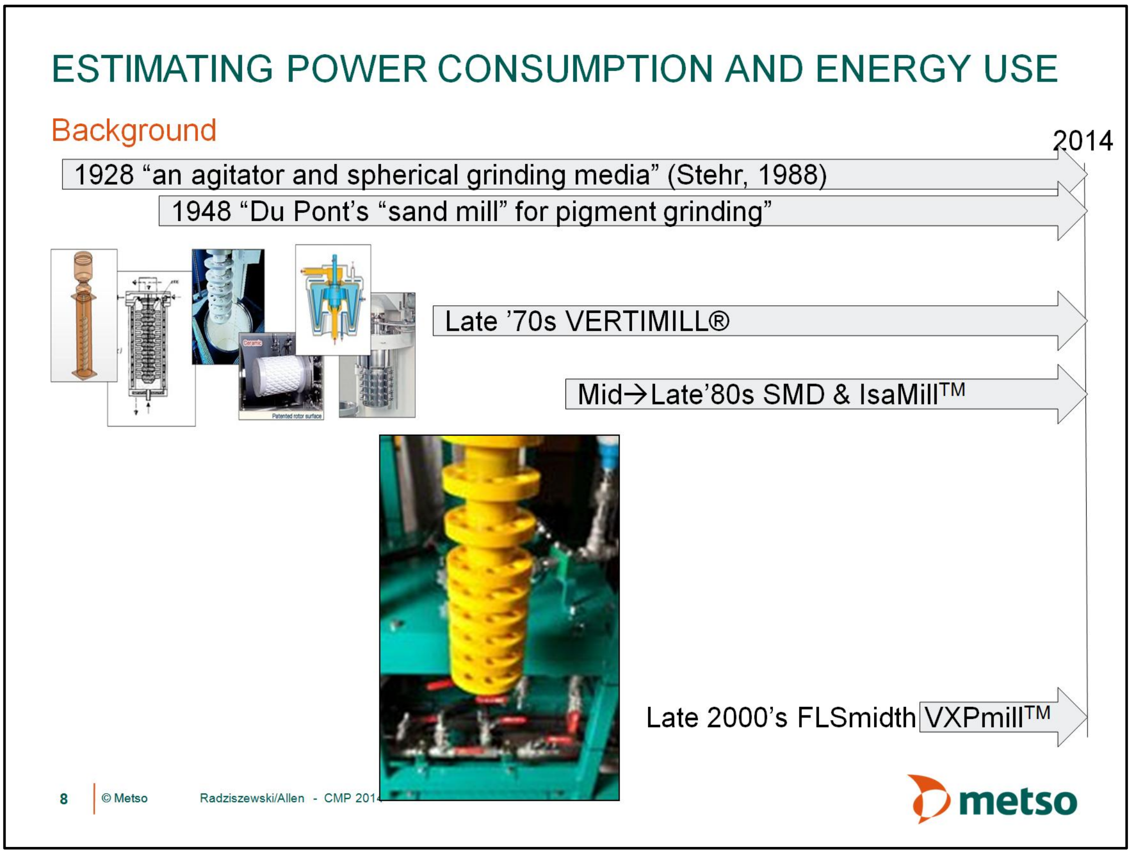
Stirred mill technology was introduced back in the late 1920’s. However, it really to DuPont’s “sand mill” for pigment grinding to start the technological development of stirred milling technologies in the fine, ultrafine and nano-scale grinding applications in industrial materials and pharmaceuticals. This development spans screw agitated mills, pin / counter pin mills, MaxxMills and angular gap mills...



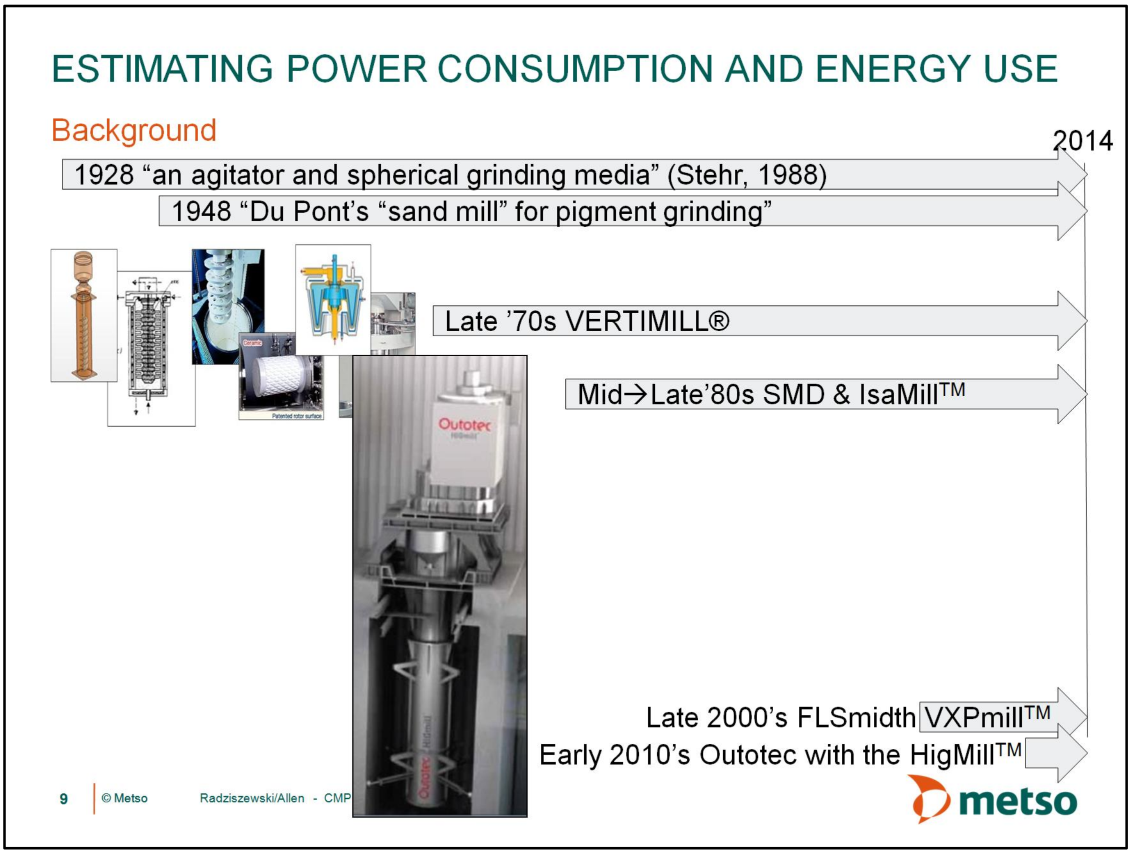
In the context of the mining industry, smaller grain size and other mineralogical characteristics have motivated the need to grind finer which has motivated the evolution of industrial mineral stirred mills to be adapted to the poly-metallic mineral applications. To illustrate this point, the VERTIMILL® was introduced to the mining industry some 35 years ago



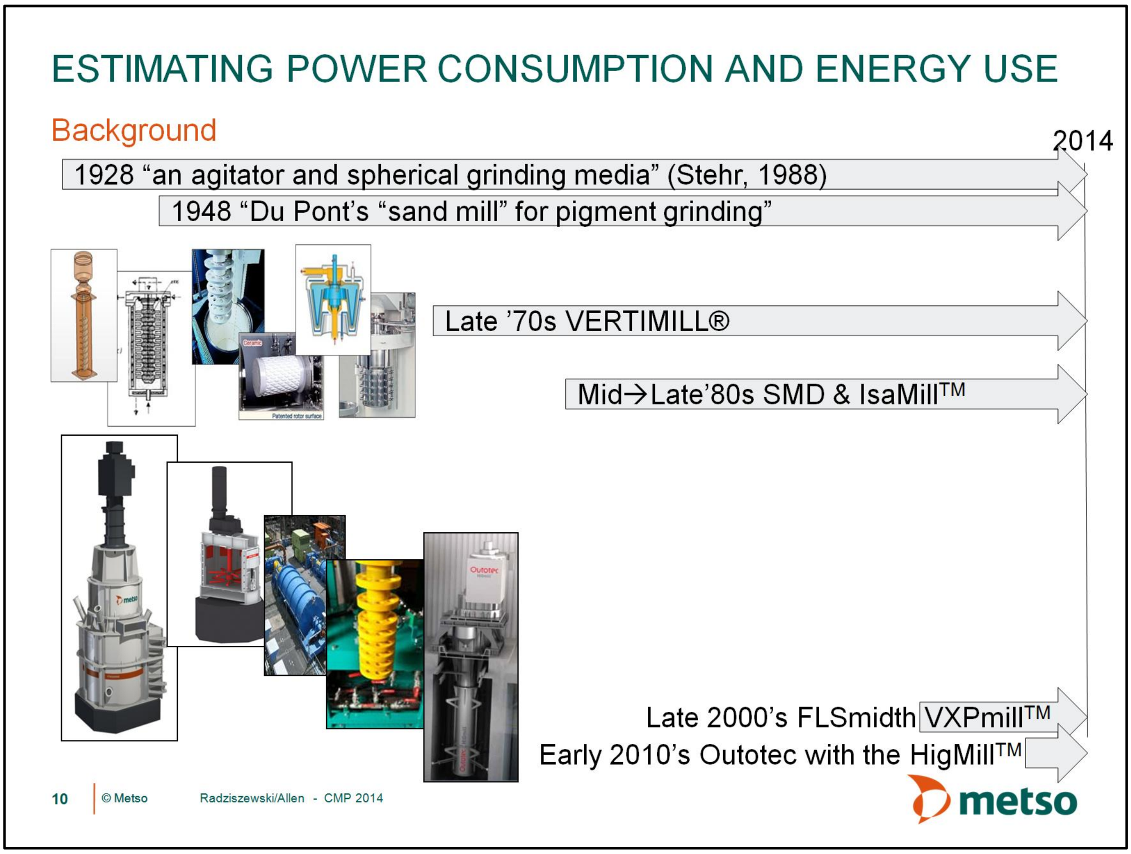
followed by the SMD and the IsaMill™ some 20 years later.



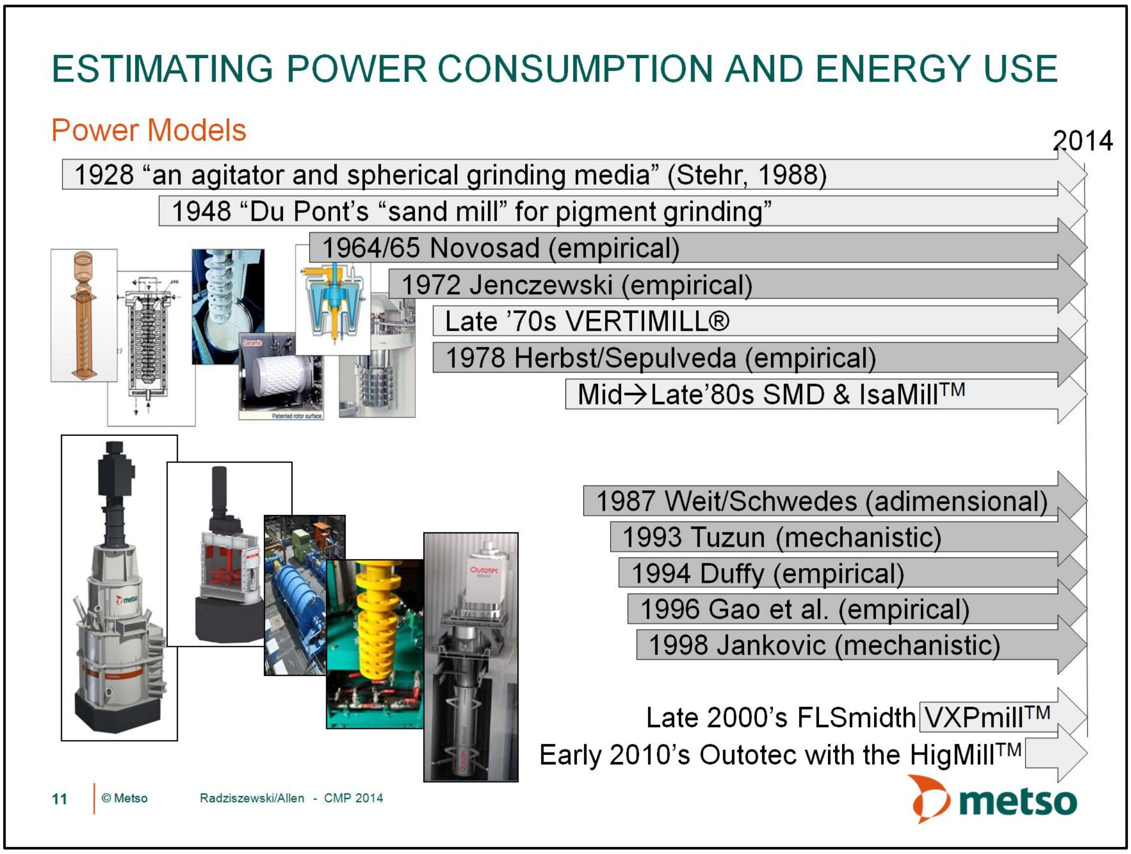
The FLSmidth VXPmill^{TM} (formerly the Deswik mill) saw its inception into the mining industry some 5 years ago



followed by the most recent entry from Outotec with the HigMill™ joining the mining effort last year.

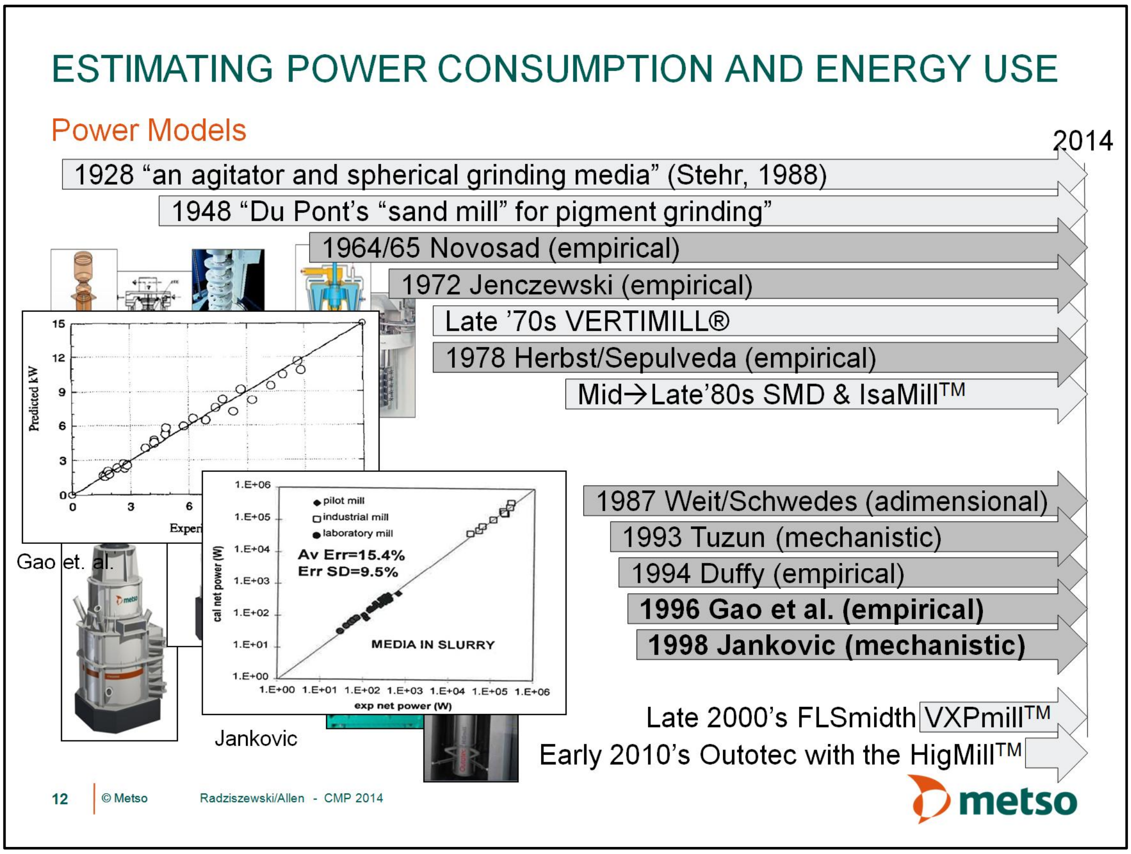


It should be note that this evolution from industrial mineral to poly-metallic mineral applications was accomplished by considering not only mechanical design but also practical operational ranges, manufacture optimizations and limitation, and economic considerations. In many cases, stirred mills are simply scaled up by holding key variables constant and correlating operation performance between machines, power models and, where available, DEM simulation results – the focus of the remainder of the presentation. Additionally, stirred milling power draw is significantly affected by the mass of the media in the mill and the machines are designed with flexibility such that media can be added as required to achieve the desire mill power consumption.



The development of power models followed the development of stirred milling technology.

Jankovic (1998) completed quite a broad literature search finding a number of stirred mill power models which include empirical models (Novosad, 1964, 1965, Jenczewski, 1972, Herbst and Sepulveda, 1978, Duffy, 1994, Gao et al. 1996), adiminsional models (Weit and Schwedes, 1987) and mechanistic models (Tuzun, 1993) into which his own work fits.



The development of power models followed the development of stirred milling technology.

In all cases, the power models were validated using data obtained for lab scale and in some cases industrial mills.

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Power Models

	Novosad (1964, 1965)	Jenczewski (1972)	Herbst, Sepulveda (1978)	Weit, Schwedes (1987)	Tuzun (1993)	Duffy (1994)	Gao (1996)	Jankovic (1999)
Impellor speed	x	x	x	x	x	x	x	x
Mill diameter	x	x	x	x	x			x
Slurry density	x			x	x		x	x
Media depth	x		x		x	x		x
Impellor diameter	x	x				x		x
Charge density	x				x	x		x
Media density			x				x	x
Media top size			x			x		x
Shaft diameter	x			x				x
Number of screw Helixes						x		x
Friction								x
Media Mass		x						x
Screw pitch								x
Length of impellor				x				
Screw thickness								x
Thickness of pins	x							
Viscosity				x				
Disperant							x	

This table illustrates the different variables used in many of these models. The only commonality between these models is the use of impellor speed as one of the model variables. Mill diameter is also shared by most models, but not all. This is followed by either media depth (or volume) and slurry density. Only Jankovic's model uses 14 of the 18 variables listed.

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Power Models

	Novosad (1964, 1965)	Jenczewski (1972)	Herbst, Sepulveda (1978)	Weit, Schwedes (1987)	Tuzun (1993)	Duffy (1994)	Gao (1996)	Jankovic (1999)
Impellor speed	x	x	x	x	x	x	x	x
Mill diameter	x	x	x	x	x			x
Slurry density	x			x	x		x	x
Media depth	x		x		x	x		x
Impellor diameter	x	x				x		x
Charge density	x	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	x
Media density		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	x
Media top size		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	x
Shaft diameter	x	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	x
Number of screw Helixes		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	x
Friction		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	x
Media Mass		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	x
Screw pitch		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	x
Length of impellor		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
Screw thickness		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	x
Thickness of pins	x	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
Viscosity				x				
Disperant							x	

But what about the effect on stirred mill power of mill shape, number of pins or disks, thickness of pins or disks, media size and shape, particle size and density, media, liner and chamber wear, gravity, ... ?

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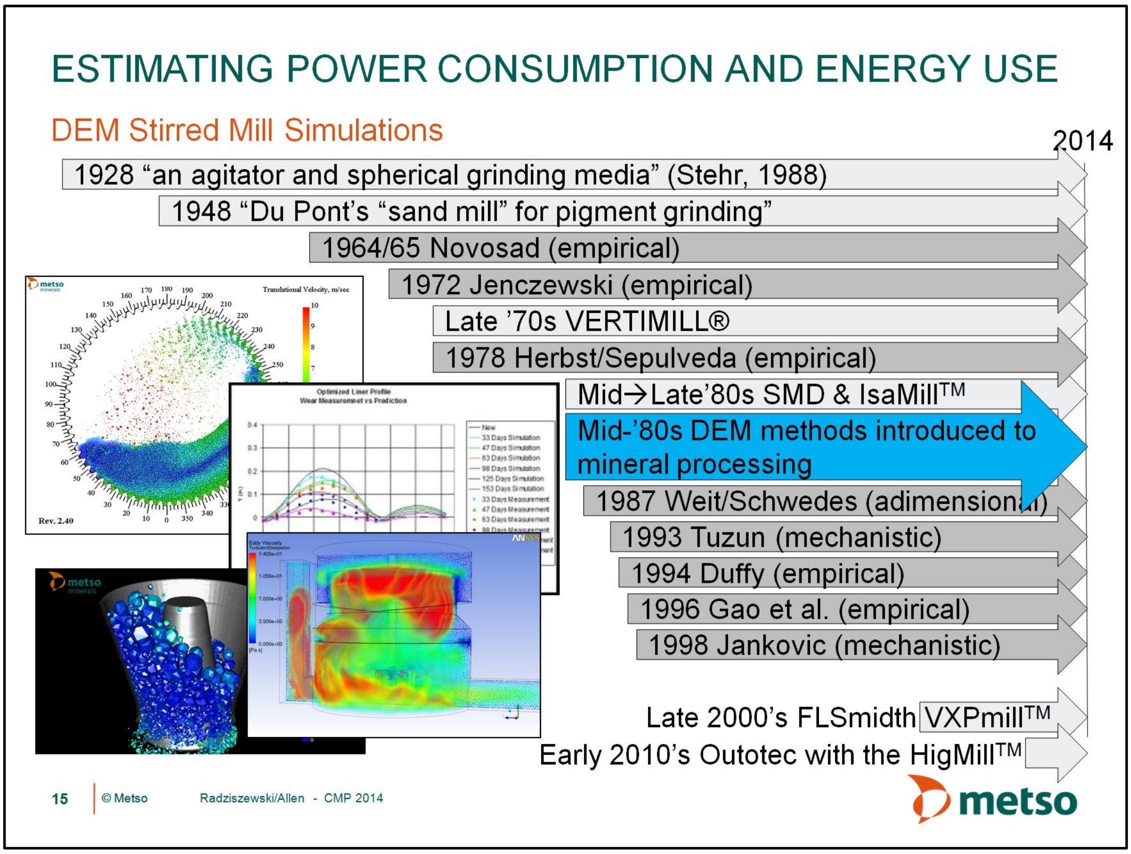
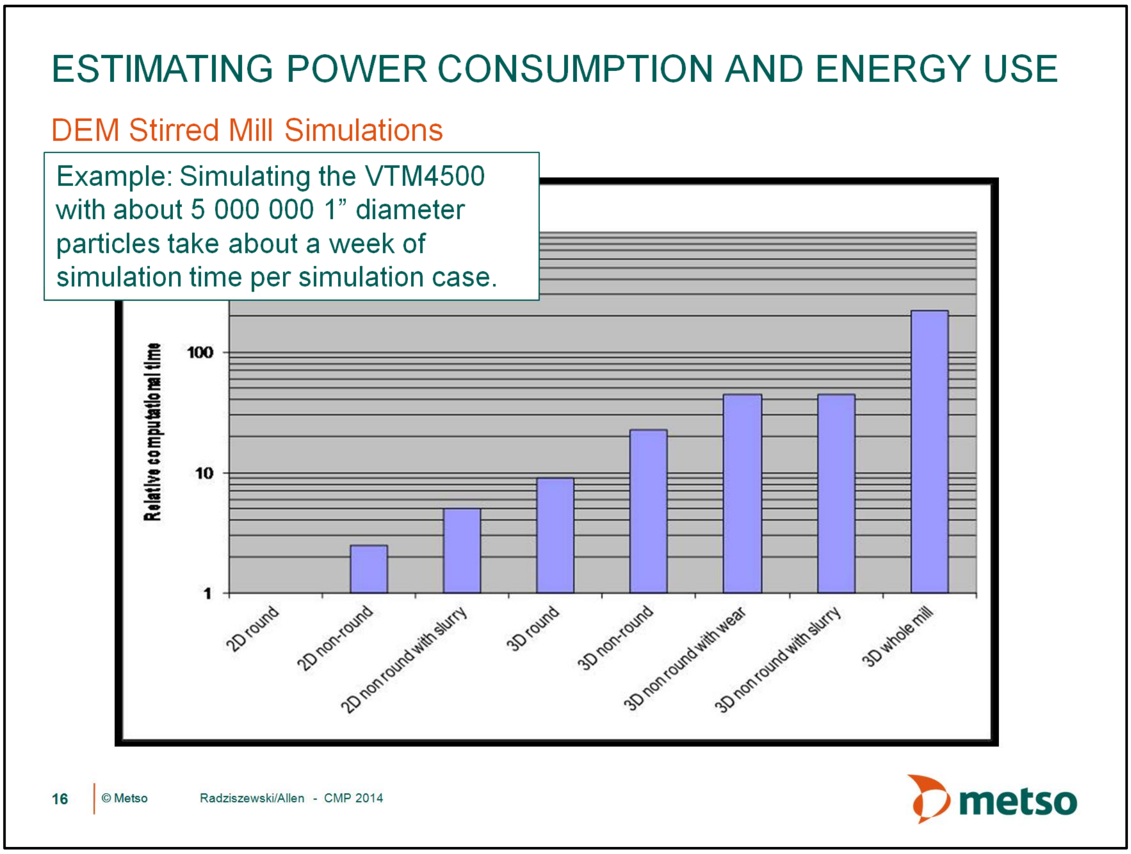
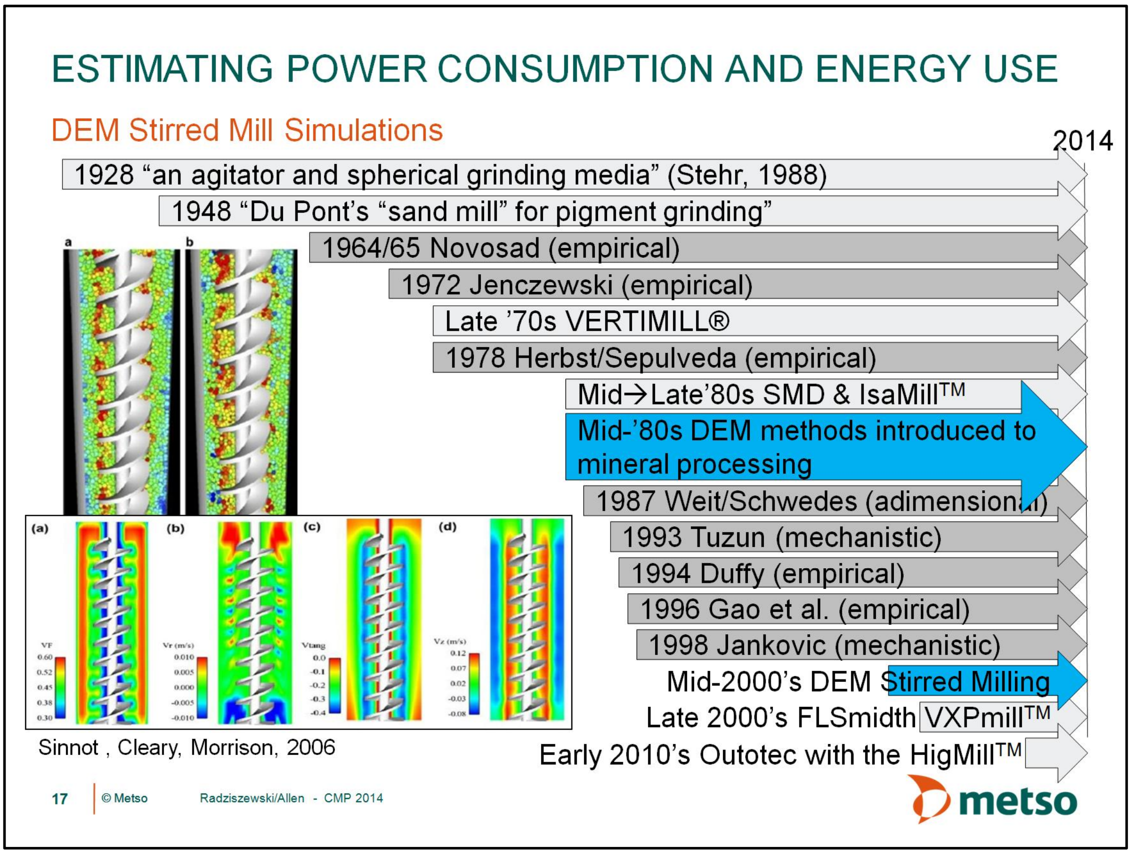
On the other hand, operational experience of the Vertimill has shown that a number of other variables not included in these models affect power draw. These missing variables may explain why outside of the mills and conditions tested, these models lack the precision needed for the scale of mill currently being manufactured and developed. Missing variables include media size distribution, media shape, particle size, rock density, media wear, impellor wear, liner wear and gravity. To complete the list one can also add variables describing mill shape, number of pins and disks and thickness of disks.



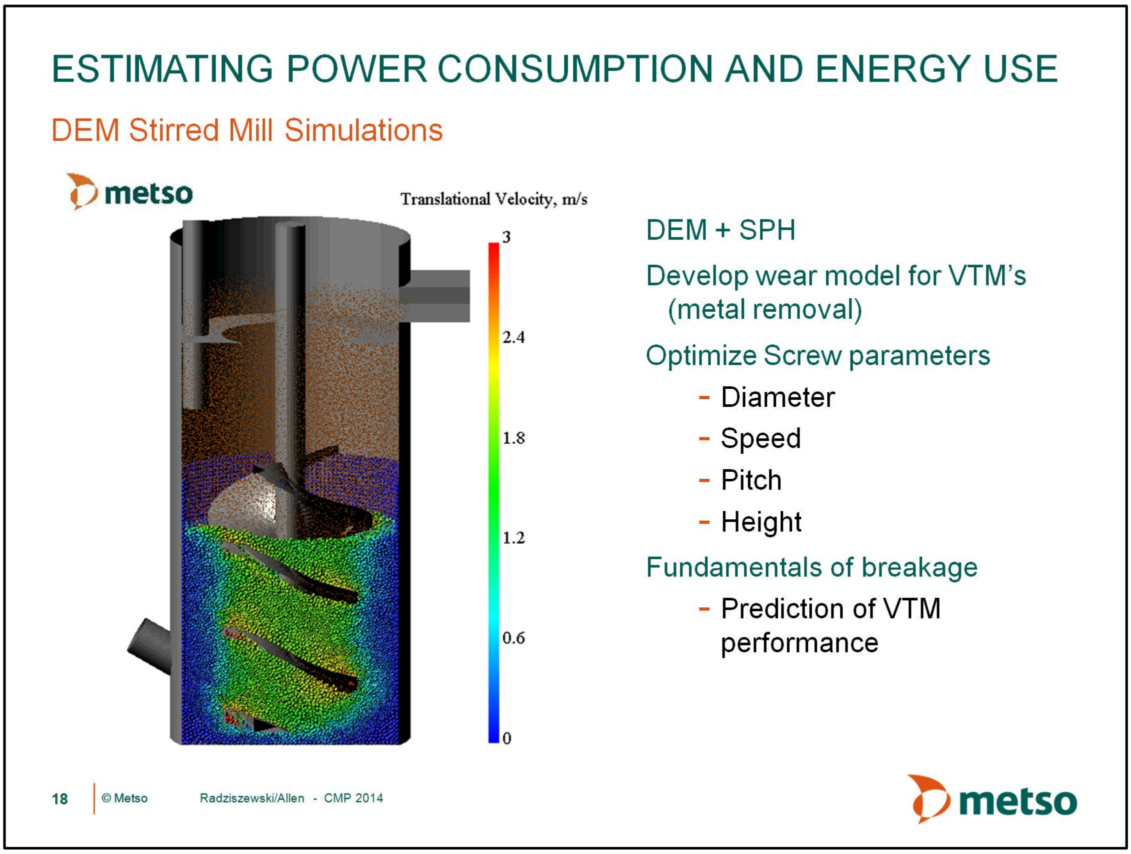
The advent of the discrete element method (DEM) and its introduction to the modelling of mineral processes opened the door to exploring in yet greater detail the dynamics of these systems. This has been successfully demonstrated through modelling of SAG mill charge motion, liner wear and crusher dynamics. Further, the introduction of computation fluid dynamics (CFD) as well spherical particle hydrodynamics (SPH) led to the modelling of flotation cell behaviour.



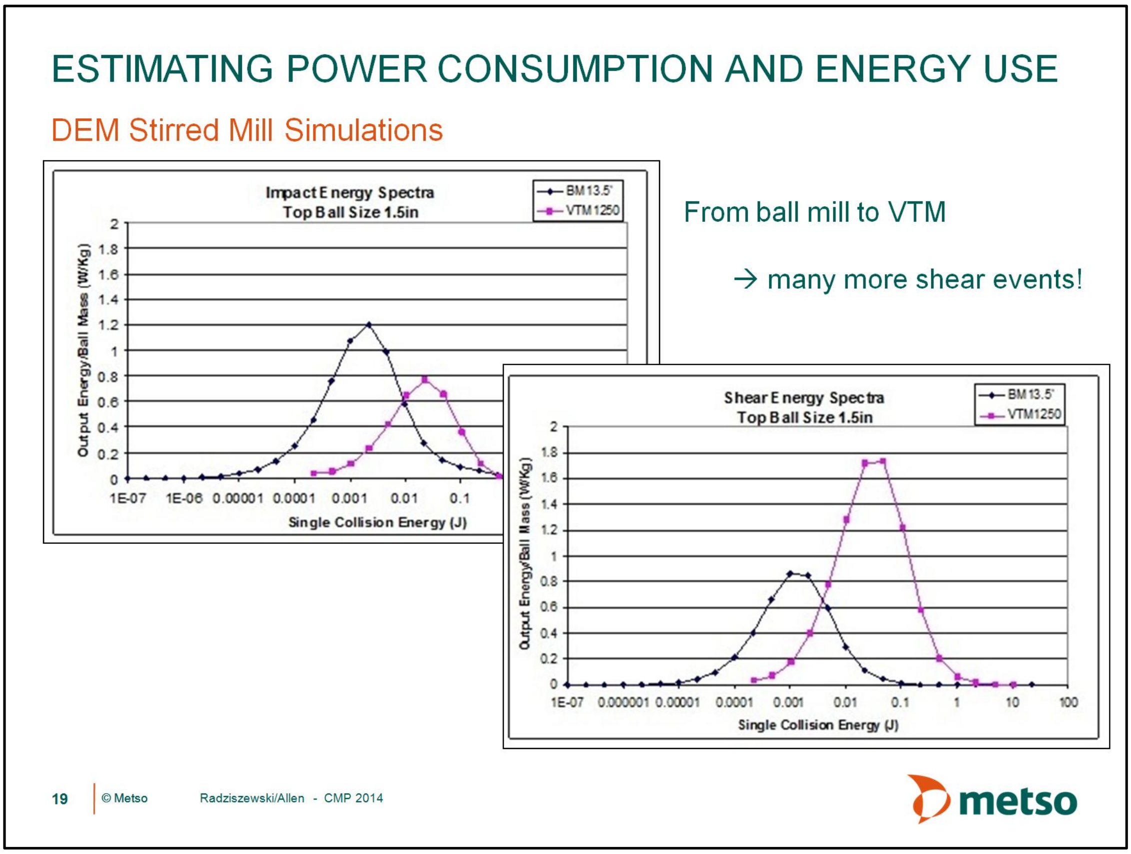
As the detail of the DEM/CFD/SPH models increase, the numerical effort or intensity as measured by computation time and number of processors required needed to simulate increases. A case in point is the simulation of a VTM4500 with 5,000,000 1” diameter media takes about a week to simulate.



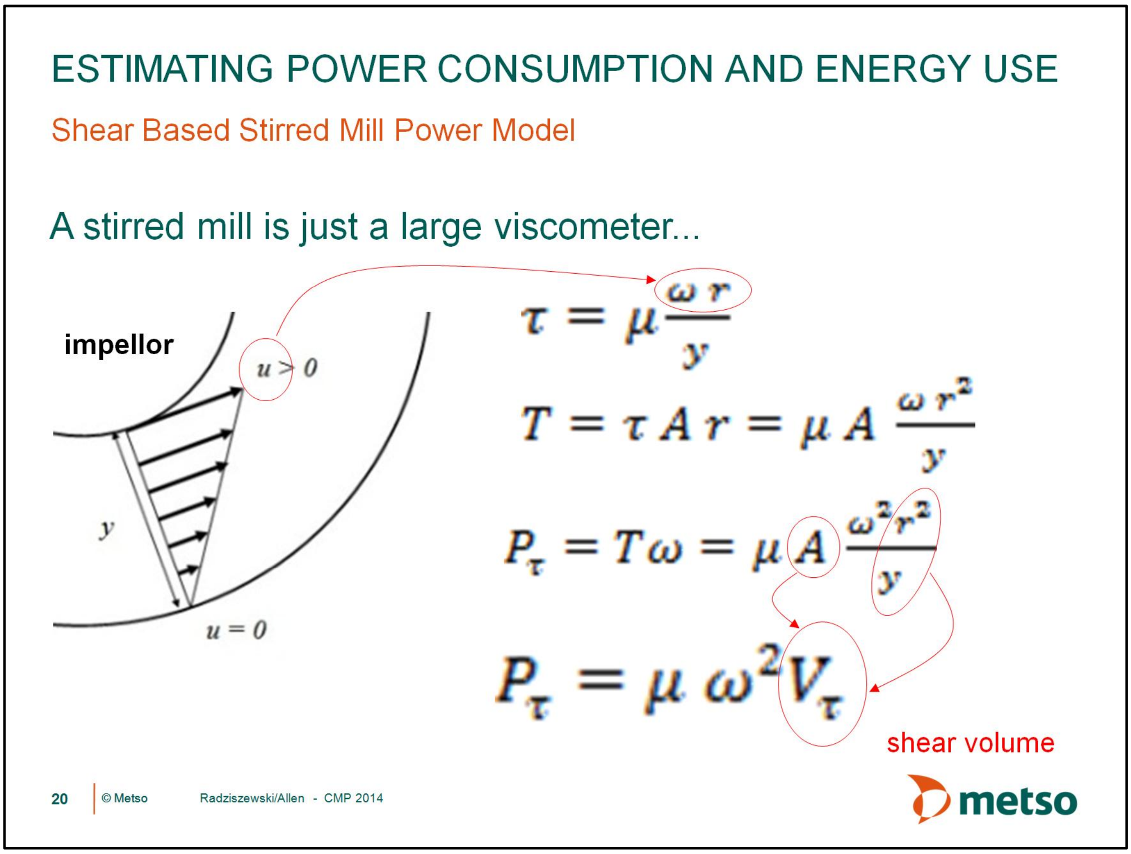
As a result, DEM/CFD simulations of stirred mills did not appear in the literature until the mid-2000's with works from Cleary's CSIRO group.



At the CMP 2013 roundtable, all manufacturers present underlined their use of advanced numerical methods such as DEM to develop and better understand their technologies. In Metso's case, these capabilities are found in the HFS group in Colorado Springs.



One of the main insights that DEM simulations provide is the comparison of the importance of impact type events to shear type events in ball mills and stirred mills (VTM in the case illustrated). This difference may be one of the reasons why stirred milling might be more efficient than ball milling.



However, from an understanding point of view, not everybody has a super computer in their back pocket...

...therefore can we use the DEM insight to orient the development of a simple mechanistic shear based model that can be programmed into a spreadsheet?

Consider the following analogy: ...a stirred mill (any stirred mill with a concentric impellor) is just a large viscometer!

As a large viscometer, shear theory is applicable and leads to the definition of a shear based stirred mill power model.

Knowing the shear stress experienced by the rotating surface, it then becomes possible to determine the torque acting on this cylinder and more importantly the power consumed in rotating the cylinder at a given speed. Putting all components together and rearranging, the power consumed by a smaller diameter concentric cylinder can be described by the fluid viscosity, the square of the rotation angular speed and a term coined the "shear volume" which is an agglomeration of all of the previous physical parameters describing all the shear surface pairs created between an impellor and the mill chamber

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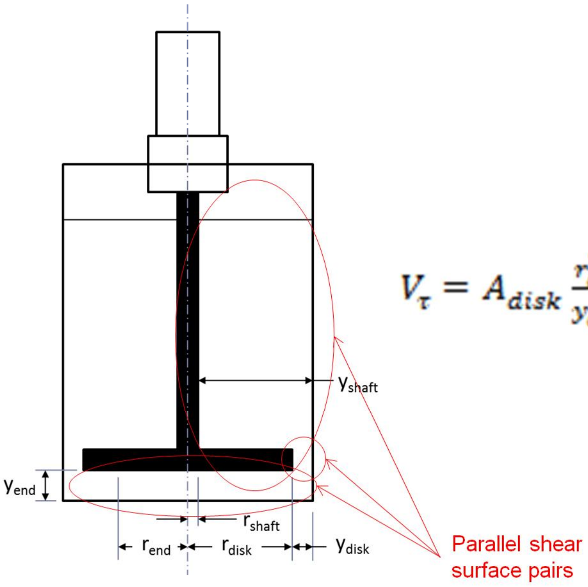
Shear Based Stirred Mill Power Model



$$V_\tau = A_{disk}\frac{r_{disk}^2}{y_{disk}} + A_{shaft}\frac{r_{shaft}^2}{y_{shaft}} + A_{end}\frac{r_{end}^2}{y_{end}}$$

Determining the shear volume of a mill starts by determining where are the parallel shear surface pairs. In the case of a one disk impellor there would be three such pairs.

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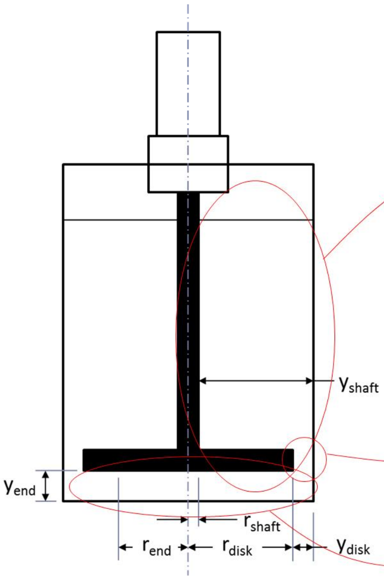
Shear Based Stirred Mill Power Model



$$V_\tau = A_{disk}\frac{r_{disk}^2}{y_{disk}} + A_{shaft}\frac{r_{shaft}^2}{y_{shaft}} + A_{end}\frac{r_{end}^2}{y_{end}}$$

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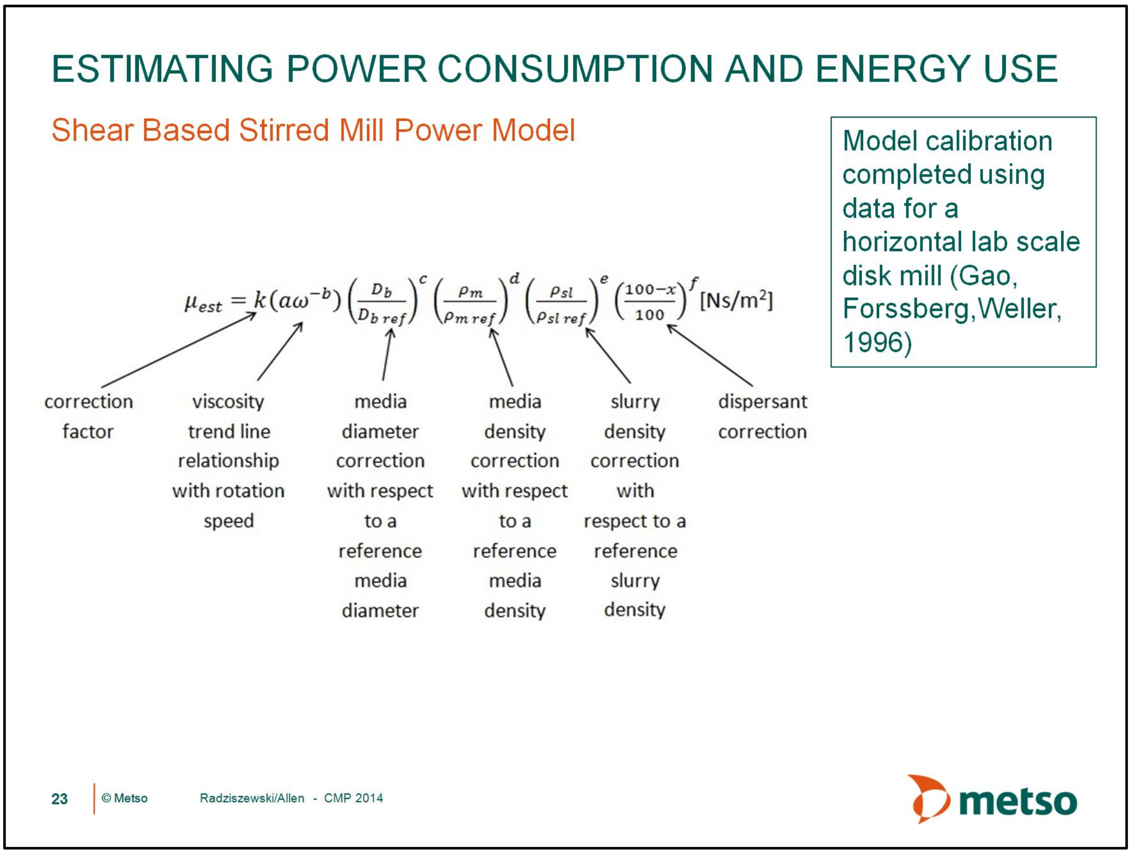
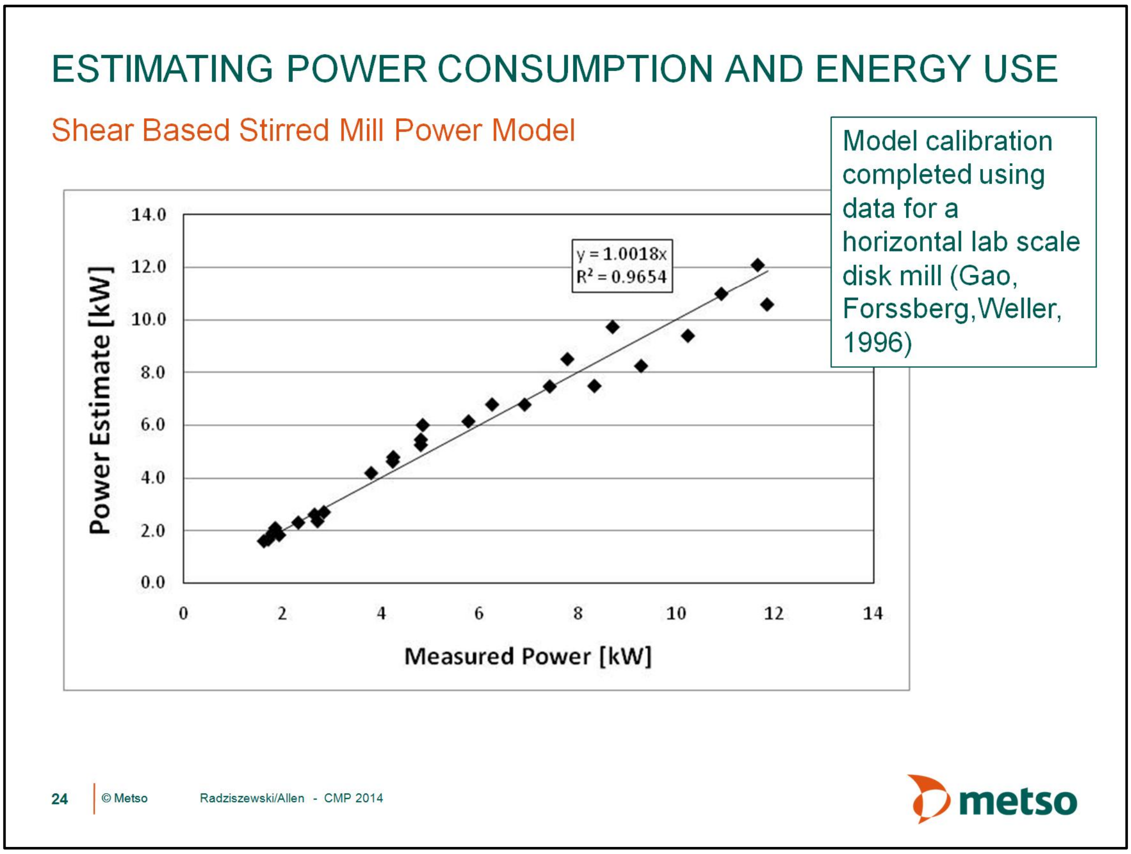
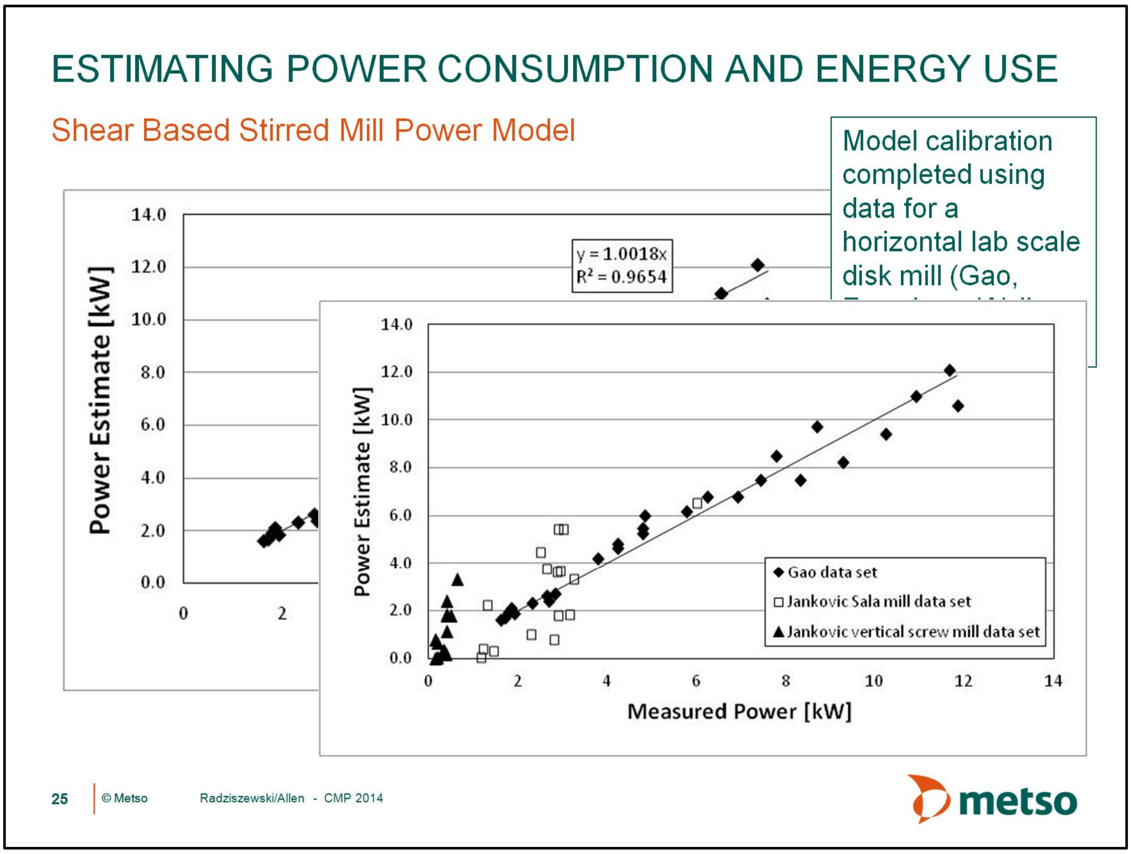
For each parallel shear surface pair, a shear volume calculation can be made. The sum of these would define the shear volume for the mill.



Confidence in the use of this viscometer stirred mill analogy to describe all concentric type stirred mills can be only determined by applying it to different stirred mills and comparing the predicted power results with that observed. This requires that a viscosity model be determined through a power calibration. This was made possible by using the data set produced by Gao et al. (1996) along with the model described in equation (2) leading to the following viscosity equation



With the appropriate reference values, constants and exponents (Radziszewski, 2013), it is then possible to calibrate the model with Gao's data.



Once calibrated, the resulting model was used to predict the power consumption a Sala mill and a vertically stirred screw mill as determined by Jankovic (1998).

These results, despite the scatter for the Sala mill and the vertical screw mill, illustrate that a shear based model seems to describe quite adequately the power consumption across a range of stirred mills.

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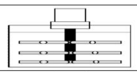
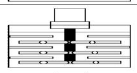
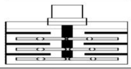
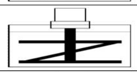
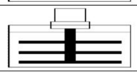
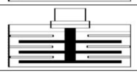
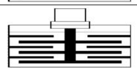
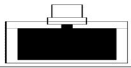
Shear Based Stirred Mill Power Model

Mill Type	Dimensions	Sketch	Shear Volume [m^3]	Shear Power Low Speed (100 rpm) [kW]	Shear Power Med. Speed (500 rpm) [kW]	Shear Power High Speed (1000 rpm) [kW]
3 x 6 Pin Impellor	pin length: 0.4m; pin dia.: 0.1m; shaft dia.: 0.2m		0.114	0.37	0.367	0.989
Pin on Pin	same as 3 x 6 pin impellor plus liner pin length: 0.3 m; thickness: 0.1m		0.150	0.048	0.483	1.301
Pin on Disk	same as 3 x 6 pin impellor plus liner disk inside dia.: 0.4 m; thickness: 0.1m		0.355	0.115	1.143	3.078
Auger	auger dia.: 0.8m; no. of turns: 1		0.466	0.151	1.502	4.044
3 Disk Impellor	disk dia.: 0.8m; disk thickness: 0.1m; shaft dia.: 0.2m		1.618	0.523	5.213	14.037
Disk on Pin	same as 3 disk impellor plus liner pin length: 0.3 m; thickness: 0.1m		2.079	0.672	6.699	18.038
Disk on Disk	same as 3 disk impellor plus liner disk inside dia.: 0.4 m; thickness: 0.1m		2.503	0.809	8.066	21.720
Drum	dia: 0.8m; length.: 0.9m		4.021	1.299	12.957	34.888

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As a result, it is possible to explore the effect of the stirred mill design space (Radziszewski, 2013) on power consumption using a 1m diameter by 1 m high chamber. For this comparison viscosity is assumed to be the same for all constant speed cases. The results of this comparison is found in this table where the shear volume for different impellor configurations as well as the expect power consumption for low, medium and high speed applications is presented.

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Shear Based Stirred Mill Power Model

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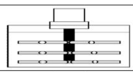
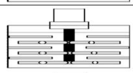
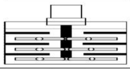
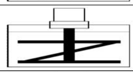
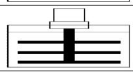
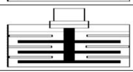
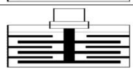
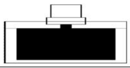
3 x 6 Pin Impellor	pin length: 0.4m; pin dia.: 0.1m; shaft dia.: 0.2m		0.114	0.37	0.367	0.989
Pin on Pin	same as 3 x 6 pin impellor plus liner pin length: 0.3 m; thickness: 0.1m		0.150	0.048	0.483	1.301
Pin on Disk	same as 3 x 6 pin impellor plus liner disk inside dia.: 0.4 m; thickness: 0.1m		0.355	0.115	1.143	3.078
Auger	auger dia.: 0.8m; no. of turns: 1		0.466	0.151	1.502	4.044
3 Disk Impellor	disk dia.: 0.8m; disk thickness: 0.1m; shaft dia.: 0.2m		1.618	0.523	5.213	14.037
Disk on Pin	same as 3 disk impellor plus liner pin length: 0.3 m; thickness: 0.1m		2.079	0.672	6.699	18.038
Disk on Disk	same as 3 disk impellor plus liner disk inside dia.: 0.4 m; thickness: 0.1m		2.503	0.809	8.066	21.720
Drum	dia: 0.8m; length.: 0.9m		4.021	1.299	12.957	34.888

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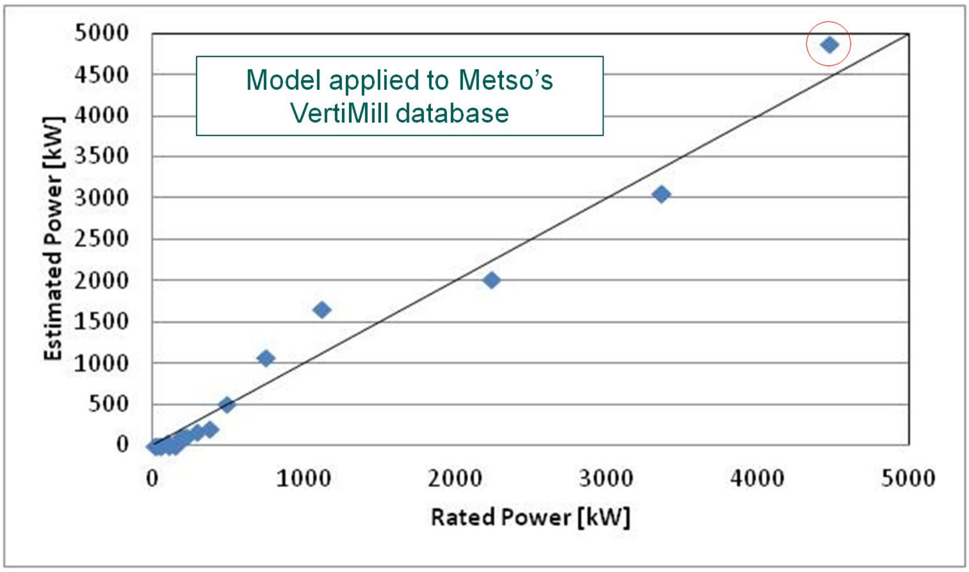
Examining this table leads to a few observations for this 1m x 1m mill context:

(i) The pin impellor has the lowest shear volume while the drum has the highest.
(ii) Pin impellor shear volume can be increased by added pins or disks to the chamber wall.
(iii) The auger (single pitch) has three times less shear volume than a 3 disk impellor.
(iv) A disk impellor shear space can be increased by adding pins or disks to the chamber wall.

Lower shear volume can be compensated by higher impellor rotation speeds. So a pin mill having a lower shear volume than an auger can actually have a higher grinding intensity than the auger mill which turns as a lower rotational speed.

ESTIMATING POWER CONSUMPTION AND ENERGY USE

Shear Based Stirred Mill Power Model



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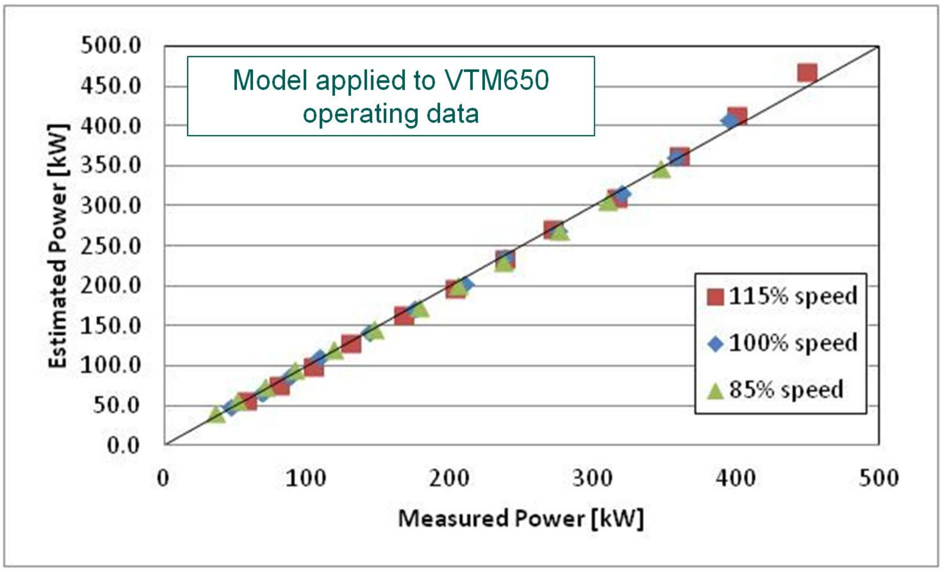
Although these results are quite interesting from a comparison point of view, the contribution to a general "comfort level" can really only be accomplished by investigating the use of this shear based model with industrial scale mills.

Therefore, applying this model to Metso's VertiMill database with some adjustments led to the comparison illustrated.

Note that the mill represented by the circled data point actually does not exist. However, if it were to exist with the possible physical and operating parameters attributed to it the shear power model would produce that power estimate.

ESTIMATING POWER CONSUMPTION AND ENERGY USE

Shear Based Stirred Mill Power Model



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Further, this model with some adjustments can be used to predict mill power as a function of mill filling as illustrated in this figure. Although the comparison between predicted and measured is not perfect, the model does show that it quite adequately predicts mill power for the VertiMill.

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Discussion

	Novosad (1964, 1965)	Jenczewski (1972)	Herbst, Sepulveda (1978)	Weit, Schwedes (1987)	Tuzun (1993)	Duffy (1994)	Gao (1996)	Jankovic (1999)	DEM & CFD	Shear based model
Impellor speed	x	x	x	x	x	x	x	x	x	x
Mill diameter	x	x	x	x	x			x	x	x
Slurry density	x			x	x		x	x	x	x
Media depth	x		x		x	x		x	x	x
Impellor diameter	x	x				x		x	x	x
Charge density	x				x	x		x	x	x
Media density			x				x	x	x	x
Media top size			x			x		x	x	x
Shaft diameter	x			x				x	x	x
Number of screw Helixes						x		x	x	x
Friction								x	x	
Media Mass		x						x	x	x
Screw pitch								x	x	x
Length of impellor				x					x	x
Screw thickness								x	x	x
Thickness of pins	x								x	x
Viscosity				x					x	x
Disperant							x		x	x
Mill shape									x	x
Number of pins									x	x
Number of disks									x	x
Thickness of disks									x	x
Media size distribution									x	
Media shape									x	
Particle size									x	
Rock density									x	x
Media wear									x	
Impellor wear									x	
Liner wear									x	
Gravity									x	x

Shear based model is somewhat better than previous power models, but still comes short as compared to potential of DEM/CFD models.

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Starting with stirred mill power models found in the literature, evolving to DEM/CFD/SPH models of the stirred mill and then back to the development of a mechanistic shear based model, the number of variables included in power modelling has evolved somewhat from that presented in Table 1. Illustrated here (Table 3), there are 30 variables listed with DEM/CFD/SPH models having the potential to simulate the effects of all of them on stirred mill power. The shear based power model currently uses some 23 variables of the 30 indicated.

Is this sufficient to simulate a stirred mill for design?

Maybe and maybe not.

Maybe, because this shear based model is indeed a function of a large number of design and operating parameters and allows a rather quick indication of how different design parameters affect power consumption.

Maybe not, because many more parameters along with impact type events are not included and those that are included namely viscosity have a very important effect on mill power. The precision required for design probably will not be adequate as compared with DEM/CFD/SPH predictions. Further research is required especially with respect to the effect of viscosity, wear and ore breakage on power.

It should be noted that some of this research is undergoing in collaboration with the JKMRC which is completing a number of industrial surveys as well as the testing of a new Metso stirred mill lab testing apparatus and methodology.

ESTIMATING POWER CONSUMPTION AND ENERGY USE

Conclusions - Insights

- Although stirred mills are in many cases simply scaled-up by holding key variables constant and correlating operation performance between machines, power models and, where available, DEM simulation results, stirred mills are typically designed with flexibility such that media can be added as required to achieve the desire mill power consumption.
- Empirical, adimensional and mechanistic stirred mill power models developed over time are limited in number of variables used which reduce their applicability to predict power in industrial scale mills being designed and developed today.
- DEM/CFD/SPH models of stirred mills hold the potential to simulate the effects of all possible variables affecting mill design and performance.
- DEM simulation results indicate that the difference in impact and shear energy spectra of ball mills as compared to VertiMill may explain the increased efficiency of VertiMill over ball mills.
- The cost of DEM/CFD/SPH models may be a hindrance to developing an increased “comfort level” in the implementation and use of stirred milling technologies in the mining industry.
- The development of a simplified shear based stirred mill power model holds the potential to simulate the effects of an increased number of stirred mill variables.
- Initial results for both lab and industrial scale mills indicate that a shear based stirred mill power model predicts mill power quite well for the cases simulated.

ESTIMATING POWER CONSUMPTION AND ENERGY USE

Conclusions - Future Work

It is currently unclear as to the value of this shear based model has for stirred mill design purposes especially as compared with the completeness of DEM/CFD/SPH modelling of stirred mills. More research is required and is undergoing.

However, in the context of meeting this paper's objective to "contribute to increasing the general comfort level with stirred milling technologies by developing a better understanding of how power and energy is affected by stirred mill impellor design and mill operation", the use of the shear based stirred mill power model may indeed be warranted.

ESTIMATING POWER CONSUMPTION AND ENERGY USE

Acknowledgements

The authors would like to thank Metso as well as an undisclosed client for granting permission to publish and present this work and associated results.

Further, the authors would like to acknowledge the work of the HFS team for the DEM/CFD/SPH results presented here.

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