A Unifying Spatial Curvature Framework for Coordinated Pass Scheduling, Shape Targeting and Mill Setup

Pass schedules, shape targets and a mill's setup are inherently coupled. Traditional design strategies partition the problem and treat these components independently, leading to undesirable interactions with no design guidance for resolving the induced difficulties. This article examines a new method that combines and coordinates these components within a unifying spatial curvature framework that abstracts from the mill type and longitudinal/transverse geometry, and provides specific design guidance.

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In reversing, multi-pass, cold rolling operations, the designed scheduling of the individual pass reductions and shape targets are inherently coupled with the mill setup (i.e., the selection of the rolls' mechanical crowns) and the material's evolving geometry and work hardening. The multi-variable operating point of each pass is a carefully orchestrated group of designed settings that achieve the rolling objectives (e.g., reduction, shape, production throughput, etc.) within the capacity of the mill and the shape actuation equipment. For these longitudinal and transverse conditions to be simultaneously achieved over the entire pass-to-pass sequence, the scheduled reductions (and separating force-induced mill/roll deformations), material's work hardening and change in cross-section geometry (aspect ratio) must coincide with the progression of the shape targets, all within the control ranges of the shape actuation.

At first glance, the design processes involved in mill setup, pass scheduling and shape targeting appear as unfathomable riddles and "black arts" of seemingly unrelated interactions and disconnected objectives. In fact, this multi-faceted design process is a complex (but understandable) sequential mechanics problem, resolvable through inferential mathematical modeling, evaluation and experience. This is a type of constrained optimization problem whose set of feasible solutions is non-unique and reminiscent of a Venn diagram intersection (i.e., there is more than one way to do the same thing). This solution variability can be a source of confusion and uncertainty on how to proceed when confronted with shape/flatness or rolling operations problems. For example:

- While rolling and engaged with the maximum positive/crown-in roll bending limit, and edge wave shape distortions still persist, should one:
  - Add more mechanical crown to compensate for the separating force–induced mill deflection?
  - Take less reduction to reduce the required separating force and ease the mill deflection?
  - Increase the entry tension to reduce the required separating force and ease the mill deflection?
  - Roll faster to reduce roll bite friction and subsequently cause the automatic gauge control (AGC) to withdraw the separating force?

These are good questions, and all are viable. Unfortunately, the family of non-unique solutions does not provide any inherent guidance on which action/direction to take, and offers no indication of the amplitude of change that is appropriate for the particular situation. Trial-and-error methods often prevail as the means of solution, and the lack of guidance can lead these explorations astray.

A new approach to this dilemma has been developed for 20-high cluster mill applications[1,2] and extended to vertical stack (4-high/6-high) configurations.[3] The key factor in these advancements is the formation of a unifying, generalized framework in which the combined pass scheduling, shape targeting and mill setup problems are posed and simultaneously resolved. The framework employs spatial curvature, vector space representations (parametric decompositions of the induced, real-world spatial stress waveforms), that are abstracted from the mill arrangement. By removing the consequences of the mill's physical arrangement and operation, this abstracted framework focuses only on the fundamental roll bite behavior, mechanical deformation and shape actuation characteristics. The combined/coordinated mill setup, pass scheduling and shape targeting design are carried out in this abstracted curvature space, and then transformed back to reality for direct implementation. The family of solutions (in this abstracted framework) provides well-defined guidance and directions of performance improvement with suggested adjustment amplitudes.[2,3]

This article examines the procedural aspects of this new approach and provides insight into the available degrees of freedom in the combined design problem. The next article in this series presents a case study showing a direct application of this new strategy.

Factors in the Design of Pass Schedules, Shape Targets and Mill Setups

Pass Scheduling — A pass schedule is a sequential, pass-by-pass series of mill reference settings and conditions that form a process by which the rolling and production objectives are achieved (typically, the desired last-pass thickness at a particular production rate). In general, pass schedule designs focus on the nominal behavior of the roll bite, reduction process and rolling conditions, formed in a longitudinal plane positioned along the centerline of the rolling axis. The result is then uniformly distributed across the transverse roll gap.[4–10] The implications of the designed reduction plan's transverse deformations are not a direct consideration. There is no coupling to the shape targeting, and the only connection to the mill setup is associated with the nominal (or mill centerline) work roll diameters.

The pass schedule's development and implementation can range from a simple tabular listing (recipe), formed from empirical findings and experience, to elaborate mathematical modeled systems employing optimization, adaptation, neural networks or genetic/heuristic algorithms.[11–14] Regardless of the method used in the design, the fundamental objective of multi-pass scheduling can be described by the following:

- Given incoming material characterized by alloy, width, thickness, yield stress, work-hardening curve, etc.
- Form a sequential reduction plan that achieves a specified total reduction or last-pass thickness.
- Operate each pass within the capacity of the mill (e.g., limits on separating force, rolling torque, tension, speed, power).
- Operate under defined constraints/conditions (e.g., bite angle, temperature, roll bite friction, maximum reduction per pass, etc.).

Figure 1 illustrates the components and operational margins involved in pass schedule development.

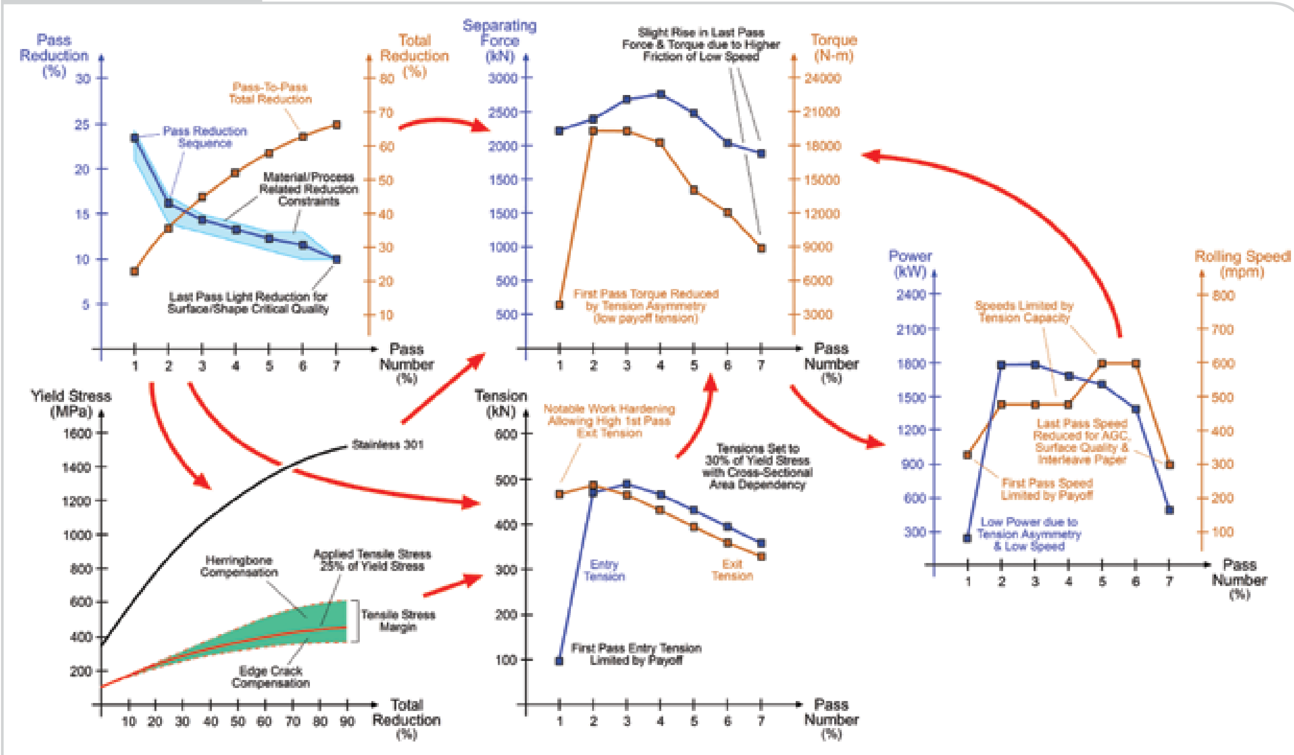
The objective is typically augmented with various criteria and considerations to further refine and direct the material processing.

- Operational criteria (productivity, reduction profiles, number of passes, final pass direction, final pass recoiling tension, etc.).
- Quality considerations (tuned later-pass reductions to assist shape/flatness, later-pass reductions and speeds to assure thickness tolerances are achieved, introduction of interleave paper, change to polished work rolls prior to rolling the last pass, etc.).

As shown in Table 1, the end result is a sequential, pass-by-pass tabular listing of nominal setpoint/reference values to be applied to the mill's control and automation system, and the individual pass' expected rolling conditions.

- Reference values:
  - Entry and exit thickness (applied to the AGC and thickness gauging system, along with the alloy composition).
  - Entry and exit tension (applied to the drive system's tension controls).
  - Rolling speed (applied to the drive system's mill speed controls).

Figure 1



Multi-pass scheduling components and relationship flows.

- Rolling conditions:
  - Separating force (can be applied to the AGC for presetting the roll gap prior to rolling the pass).
  - Rolling torque and/or power.

These values/conditions are the most basic, and many pass scheduling strategies provide an expanded parameter set.

- Rolling conditions:
  - Entry and exit yield stress (based on provided alloy work-hardening curve).
  - Forward slip.
  - Entry and exit strip temperature (possibly for feedforward and closed-loop temperature control).
- Mode selections, reference values and rolling operations:
  - AGC mode (to select the mode applied to the individual passes).
  - Roll gap sensitivities (applied to the AGC to assist in work hardening and rolling speed adaptations).
  - Tension control mode (to adjust the control strategy as the material becomes thinner).
  - Tension range (to select multi-speed gearbox ratio).
  - Shape target parameters (applied to the shape/flatness control system (AFC)).
  - Shape actuator preset references (e.g., roll bending setting, etc.).
  - Coolant control mode, pressure and flow settings (e.g., speed or power related, or strip temperature control).
  - Strip wiper mode and pressure settings.
  - Work roll surface (e.g., matte, smooth, polished, superfinish).

Shape Target Progression — A shape target describes the desired transverse differential stress pattern induced in the rolled/exit strip and is applied as a reference to the shape/flatness control system. Shape target design methods[4] operate in the transverse plane and are focused only on the rolled/exit strip, coiling processes, post-rolling phenomena, downstream process requirements and quality concerns.[4,15,16] No consideration is given to how the mill will produce these results, or whether the mill can even achieve these results.[2,3]

An intuitive notion suggests that each pass should be rolled to an ideally flat condition. However, this approach may not satisfy the multi-pass needs of the mill/material in a reversing scenario. As shown in Figure 2, the pass-by-pass shape targets may follow a progression that accommodates both the needs of the

Table 1

Pass Schedule for Rolling 1,030-mm-wide 304 Stainless Steel With a Bright-Annealed Finish on a ZR22BE-52 Mill

Basic components

	Thickness		Reduction		Yield stress		Tension				Rolling speed	Sep. force	Torque	Power
	Entry	Exit	Pass	Total	Entry	Exit	Entry	Exit	Range					
Pass	(mm)	(mm)	(%)	(%)	(N/mm^2)	(N/mm^2)	(kN)	(kN)	Entry	Exit	(mpm)	(kN)	(N-m)	(kW)
1	3.000	2.295	23.50	23.50	308	799	100	472	PO	L.Spd	330	3,226	4,215	268
2	2.295	1.926	16.08	35.80	799	988	472	490	L.Spd	L.Spd	480	3,407	19,289	1,784
3	1.926	1.650	14.33	45.00	988	1,103	490	469	L.Spd	L.Spd	480	3,691	19,332	1,788
4	1.650	1.431	13.27	52.30	1,103	1,177	469	434	L.Spd	L.Spd	480	3,774	18,294	1,692
5	1.431	1.254	12.37	58.20	1,177	1,227	434	396	M.Spd	M.Spd	600	3,487	13,978	1,616
6	1.254	1.109	11.56	63.03	1,227	1,260	396	360	M.Spd	M.Spd	600	3,043	12,222	1,413
7	1.109	1.000	9.83	66.67	1,260	1,281	360	330	M.Spd	M.Spd	300	2,907	8,927	516

Augmented components

Pass	AGC mode	AFC/shape		Coolant				Wiping		Work roll finish
					Flow (%)					
		Target curve	Gain	Mode	Bite	Strip	Outer	Base pressure	Speed gain	
1	FB	4	25	Pwr	100	100	100	70	15	Std
2	MF	4	15	Pwr	100	100	100	70	15	Std
3	MF	4	5	Pwr	100	100	80	65	15	Std
4	FFX	4	0	Pwr	100	100	75	60	17	Std
5	FFX	4	–2	Pwr	100	85	70	50	17	Std
6	FFX	7	–5	Pwr	85	75	65	40	19	Polish
7	FFX	7	–12	Temp	75	70	60	35	20	Super

Legend:
PO = Payoff reel tension/speed range; L.Spd = low-speed/high-torque range; M.Spd = mid-speed/mid-torque range; FB = feedback AGC mode; MF = mass flow AGC mode; FFX = extended feedforward (multi-mode); Pwr = power-based flowrate; Temp = strip temperature-based flowrate; Std = standard work roll surface finish; Polish = polished work roll surface finish; Super = superfinished work roll surface

material handling/tracking, material protection (e.g., from edge crack–induced strip breaks) and also the final pass delivered shape.

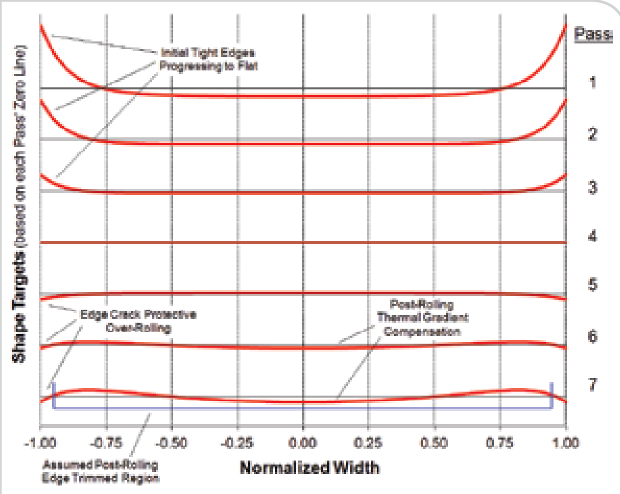
- Early passes may employ a tight-edged (slightly over-rolled center) shape target to promote good strip tracking/payoff-loading and good coil buildup.
- Intermediate passes progress to a flat shape target.
- Final passes may retain a flat shape target, or may adjust the delivered shape/flatness to assist downstream processes.[4] Depending on the level of edge crack protection and incoming strip shape requirements of the next downstream process (e.g., side trim and anneal, or ship directly, etc.), the final pass targeted shape may not be an intuitive flat spatial waveform.

Other pass-to-pass varying compensations may also be included, for example:

- Transverse thermal gradient compensation may also be augmented to the shape target to address post-rolling cooling flatness distortions.
- Coil buildup compensation may also be applied to handle strip profile-induced transverse coil diameter variations or wedged-coil diagonal stress distortions.

The individual pass shape targets may have complex transverse waveform patterns, and it is important that the overall progression provide a smooth, non-disturbing pass-to-pass transition that is within the shape actuation capabilities of the mill.[2,3] The successful achievement of the shape targets on a pass-by-pass basis is an important aspect of strip quality and mill

Figure 2



Multi-pass shape target progression.

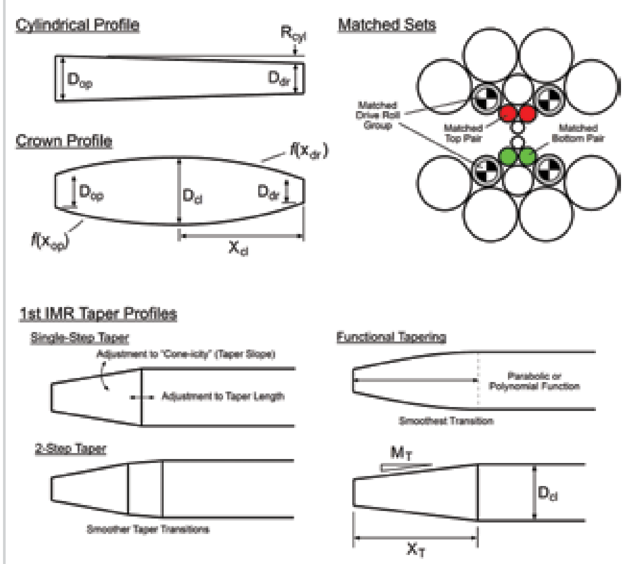
throughput (production not slowed or compromised by strip shape problems, edge crack-induced strip breaks or roll changing issues).

Mill Setup — The term "setup" denotes the determination of the individual roll's transverse diameter profile variations (i.e., crown/tapers/complex curvatures) to provide a mechanical compensation for the separating force–induced deformation of the assembled roll stack/cluster over the strip. The mill setup compensation is inherently coupled to the pass schedule and shape target progression, and is crucial to the shape control performance.

The mill setup designs operate in the transverse plane and work to achieve the broadest deformation-compensating margins, thereby reducing the extent of dynamic shape actuation. General notions of the pass-scheduled separating force behavior are the primary coupling, with some degree of late-pass shape targets being considered to make sure those quality issues can be achieved.

Errors and inconsistencies in the ground profiles of the rolls directly translate to shape distortions in the rolled strip, which may exceed the range of compensation in the available shape actuators. In addition, the roll surface finishes must adhere to specific conventions of inter-roll contact torque transmission and strip surface finish requirements. Figure 3 provides some insight into the nature of the setup for a 20-high cluster/Sendzimir mill. Note that the roll cluster setup employs a variety of mechanical crowns and tapers, providing flexibility and freedom in the setup design (which can be both good and bad). Further, full-width tapering and offset crowning may be used to compensate for deficiencies in the mill housing's transverse bore geometries.

Figure 3



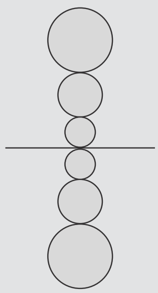
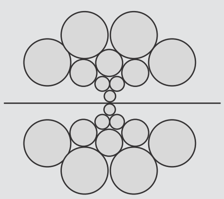
	Work rolls	1st IMRs	2nd IMRs Drive	2nd IMRs Idler
Roll profile format				
Flat	X		X	X
Flat with tapers		X	X	X
Crowned	X		X	X
Crowned with tapers			X	X
Finish				
Superfinish	X			
Polished	X	X		
Roughness (Ra) (µm)	0.2–0.3	0.3–0.5	0.3–0.6	0.3–0.5
Roll profile tolerances				
Parallelism (µm)	2.0	3.0	3.0	5.0
Crown centerline (µm)	0.3		0.3	0.3
Crown symmetry (µm)	3.0		3.0	3.0
Profile errors (µm)	2.0		2.0	2.0
Paired diam. differences (µm)		5.0		
Group diam. differences (µm)		250.0	250.0	250.0
Taper length error (µm)		100.0	100.0	100.0
Taper slope error (%)		0.01	0.01	0.01

1. For 2B material, work roll change on last pass, then use these last pass rolls to start the next coil. Change these work rolls following payoff pass.
2. For BA material, work roll change on second-to-last pass with polished finish and on last pass with superfinish. Mirror finish obtained with superfinish on last three passes.

Typical roll crown/taper parameters and surface finishes in 20-high cluster/Sendzimir mills.

Table 2

Various Degrees of Freedom Available to the Designer in Terms of Static and Dynamic Characteristics

Mill type	Rolls	Shape actuation			
			Dynamic		
		Static	Method	Pattern	Temporal
Vertical stack (6-high) 	Work	Mechanical crown			
		Roll bending preset	Roll bending	Low order	Fast
		Basic sprays	Zonal sprays	Complex high order	Slow
	Intermediate	Complex crowns	Lateral shifting	Low order	Slow
		Tapers			
		Lateral shifted preset			
		Roll bending preset	Roll bending	Low order	Fast
	Backup	Mechanical crown	Skewing/tilting	First order	Fast
		Tapers			
Cluster (20-high) 	Work	Mechanical crown			
	1st intermediate	Tapers/ complex curves	Lateral shifting	High-order edge effects	Fast
		Lateral shifted preset			
	2nd intermediate	Mechanical crown			
	Backing assembly	Mechanical crown (bearing & saddle heights)	Top crown eccentrics	Complex high order	Fast
Independent of mill type or rolls		Pass scheduled reductions and separating force–induced deflections	Changes in rolling speed – Increasing speed reduces friction and rolled exit thickness, causing the AGC to reduce separating force		Slow
			Changes in entry tension – Increasing entry tension reduces compresive yield criteria, causing the AGC to reduce separating force		Slow
		Scheduled nominal shape targets	Changes in shape targets – Programmed changes for post-rolling and coil buildup conditions		Slow

From a production throughput perspective, it is desirable to achieve the complete rolling of a coil (all passes) with a single roll stack/cluster arrangement (i.e., no inter-pass roll changes to adjust the roll stack/cluster's effective crown and resulting deformation while under load). This is always the case in vertical stack mill operations; however, in 20-high cluster/Sendzimir mills, the small, chockless work rolls can be changed quickly, providing a degree of operational flexibility. Certain precision, surface-critical rolling operations (e.g., bright-annealed (BA) stainless steels) may strategically switch to polished and superfinished work rolls on the final passes to achieve the required surface finish.[17,18] Here, the rolling operations employ scheduled inter-pass work roll changes (see Table 1). These work roll changes also provide the ability to modify the work rolls' mechanical crowns, offering a degree of freedom to the design of the shape target progression.

Degrees of Design Freedom

When developing pass schedules, shape target progressions and mill setups, the designer has to confront the multi-variable problem of anticipating an incoming strip shape, separating force–induced roll stack/cluster deformation and thermal crown behavior, and combine the shape targeting needs of the process (e.g., edge crack protection or post-rolling conditions) to define a workable series of operating points that can be accommodated by the planned mechanical crown setup and constrained shape actuators. Table 2 shows the designer's degrees of freedom, grouped in statically adjustable (off-line) and dynamically adjustable (on-line) parameters.

Statically Adjustable (Off-Line) Parameters — The objective of the static design freedoms is to combine the pass-scheduled reduction plan and the deformation compensation of the mill setup to coincide with the shape target progression, thereby requiring no dynamic compensation (i.e., dynamic adjustments hold at their nominal or preset settings). The static parameters are adjustable only when rolling operations are not under way, and can be concentrated into four primary categories:

- **Pass schedule —** See the section entitled Pass Scheduling.
- **Nominal shape target —** See the section entitled Shape Target Progression.
- **Roll stack/cluster mechanical crown setup —** See the section entitled Mill Setup.
- **Dynamic shape actuator presets —** This involves a planned variation from the nominal operating point beyond the designed deformation compensation of the roll stack/cluster mechanical crown setup to expedite production (e.g., larger reductions, fewer total passes, etc.). To compensate, the dynamic shape actuators are preset to the levels needed to counter the resulting/planned separating force–induced deformation. The planned variation in the operating point must not exceed the control range of the dynamic shape actuators and will skew the bipolar symmetry of the shape actuation correction margins.

There are two opportunities when off-line static adjustments can be applied:

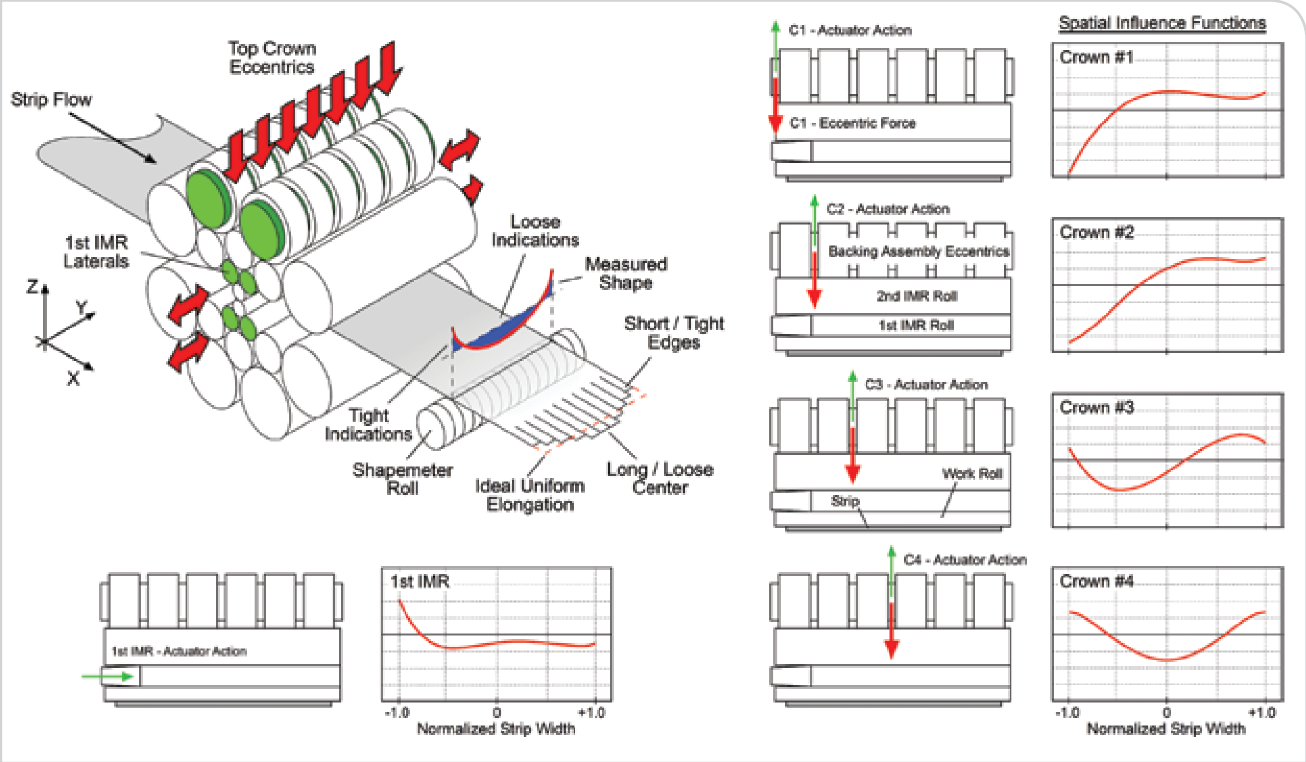
- **Inter-coil —** During non-rolling operations between coils. This is the natural point for roll changes and switching pass schedules (for all mill types), mainly to handle issues like roll wear, mechanical crown changes to accommodate different incoming materials or different production plans. In certain rolling campaigns of many similar coils, the pass schedule may remain the same or it may be optimized to accommodate a detected opportunity to improve performance and/or productivity.
- **Inter-pass —** During the line stop and reversal between passes. The chockless work rolls of 20-high/Sendzimir mills provide for rapid inter-pass roll changes, and support planned/scheduled work roll changes to facilitate strip surface treatment and/or final pass adjustment of the roll cluster's total mechanical crown. Inter-pass roll changes in vertical stack configurations (4-high/6-high) bring unwelcome production losses, and for certain operations/alloys, thermal dissipation in the waiting coiled material may lead to rolling complications (e.g., martensite morphology in metastable austenitic stainless steels,[17,18] post-rolling shape issues[15,16]). In certain "tolling" operations, the arriving coils' characterizing data may be limited to width, nominal thickness and general alloy, and parameters like yield stress may be unknown until the first pass is under way. Here, inter-pass adaptive scheduling[11] can be applied to recalculate the reduction plan as the effective work-hardening trend is exposed through rolling.

Of course, various pass-scheduled setpoints (e.g., tensions, speed, force, thickness, etc.) can be arbitrarily/experimentally adjusted while "in pass" to accommodate unforeseen rolling disturbances, or as part of experimental schedule development. Care must be taken in handling these "in-pass" changes because they can impact the behavior of adaptive pass scheduling algorithms and cause the "well-meaning" automated systems to adopt the bad habits of the operators.

Dynamically Adjustable (On-Line) Parameters — The dynamic parameters are freely adjustable during active rolling, and may be subjected to limits, constraints and operating point–induced restrictions.[1,3]

- **Dynamic shape target —** This is a controlled variation in the nominal shape target associated with compensation for detrimental or compromising conditions that may evolve during the pass. Some examples can be seen in: compensation for variations in the transverse coil diameter profile associated with the strip profile's coil buildup, or compensation for the strip's thermal characteristics primarily associated with distortions induced by post-rolling coil cooling.[15,16]
- **Shape actuators —** These devices provide the ability to adjust the roll gap's transverse compressive stress profile while rolling operations are under way. As noted in Figure 4, each shape actuator induces a unique transverse shape/stress adjustment pattern (waveform) that can be characterized by a continuous, non-linear spatial influence function.[1–3,19] The shape actuation characteristics of vertical stack and cluster mill arrangements differ significantly, in both their transverse spatial waveforms and temporal responses.

Figure 4



Shape actuation systems and spatial influence functions for a 20-high, cluster/Sendzimir arrangement.

An Analytic Means of Systematic Schedule, Target and Setup Design

Classical pass scheduling, shape targeting and mill setup design methods[4–10,20] employ differing and often detrimentally competing objectives, agendas and design disciplines. Their design methodologies are formed in mathematical frameworks and mindsets that are largely independent of the fundamental longitudinal and transverse couplings and interactions. These diverging interests create a coordination paradox, with no defined guidance toward a viable solution.

As shown in the block diagram of Figure 5, the objective of ongoing research[1–3] has been to develop a means of forming a systematic, analytic process of unifying the designs of pass scheduling, shape target progressions and mill setup, while also offering ways to address related problems and issues, which include: predicting the shape actuation capabilities (SACEs[1]), determining incoming shape requirements and resolving complex shape distortions.

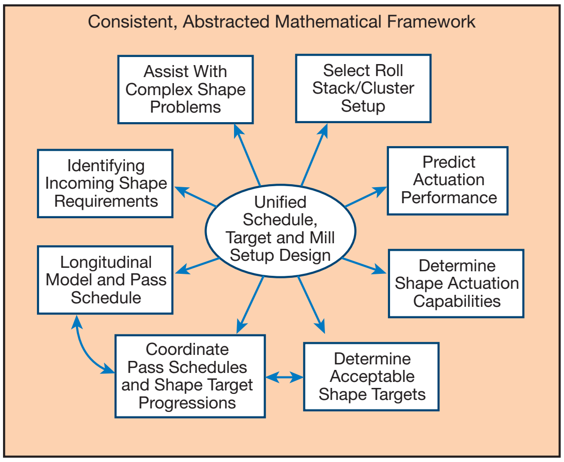
Another aspect has been to identify a methodology for addressing the coordination issues. The abstracted framework provides directions for performance improvement, much in the way a Bode diagram analysis can suggest an adjustment to the location of a transfer function pole or zero (Laplace S-Plane). These directions/suggestions form feedback-like pathways to the settings within the pass schedule, shape target progression and mill setup, where the corrective adjustments are applied.

Abstraction Through Parametric Decomposition — An important component of this work is the development of a common framework in which the analysis and designs are collectively carried out in a consistent, unifying representation (as indicated by the orange background of Figure 5). The idea is to apply a mathematical abstraction to offer a degree of independence from the mill type, shape actuation arrangement and operational practices.

The "lowest-common denominator" of coupling between the pass schedule, shape target and mill setup designs occurs in the residual or induced differential stress patterns (waveforms) formed across the transverse strip width. The waveform pattern can originate from the incoming strip's residual shape, separating force–induced roll stack/cluster deformation or the mill's shape actuation.

As shown in Figure 6, the abstraction is formed by a parametric decomposition of the real-world, measureable transverse shape/stress waveform patterns (regardless of origin) to their spatial curvature constituents, based on orthogonal polynomial representations[1–3,19] (originating from function approximation

Figure 5



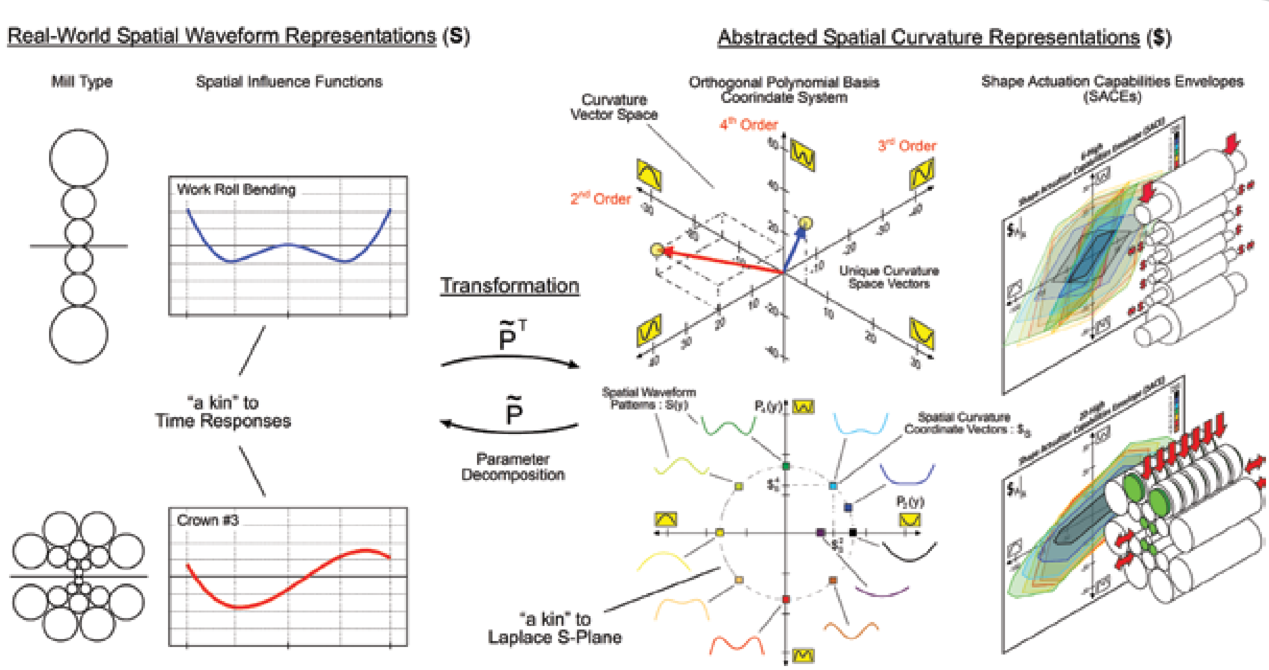
Design components, along with an underlying common framework.

theory). A spatial waveform pattern (of arbitrary origin) is uniquely characterized by a single vector within the orthogonal polynomial vector space (i.e., it is formed by a unique collection of spatial curvatures). These representations provide a convenient means of describing the spatial curvatures and form an analytically expedient vector space basis set (coordinate system). This parametric decomposition is a bi-directional transformation which allows designs and evaluations to be carried out in the curvature vector space, then transformed back to real-world spatial waveforms for direct implementation.

Coordinated Design — The coordinated design process is performed in the abstracted curvature space and focuses on satisfying the pass-to-pass shape target reachability criteria,[1–3] listed in Figure 7. The *Offset* SACE[2] defines the extent of spatial curvatures that the mill can provide (both statically, $\$_R$, and dynamically, $\$_A$) in the presence of a prescribed incoming shape, $\$_0$. Within the abstracted curvature space, and as shown in Figure 9a, the condition of shape target reachability[2,3] is satisfied when the shape target curvature, $\$_T$, resides within and is overcontained by the *Offset* SACE. In cases where the shape target is "non-reachable" (outside the *Offset* SACE), a static adjustment to the roll stack/cluster's deformation contribution, $\$_R$, must be made to either the pass schedule or mill setup by applying the degrees of freedom, discussed in earlier sections of this article.

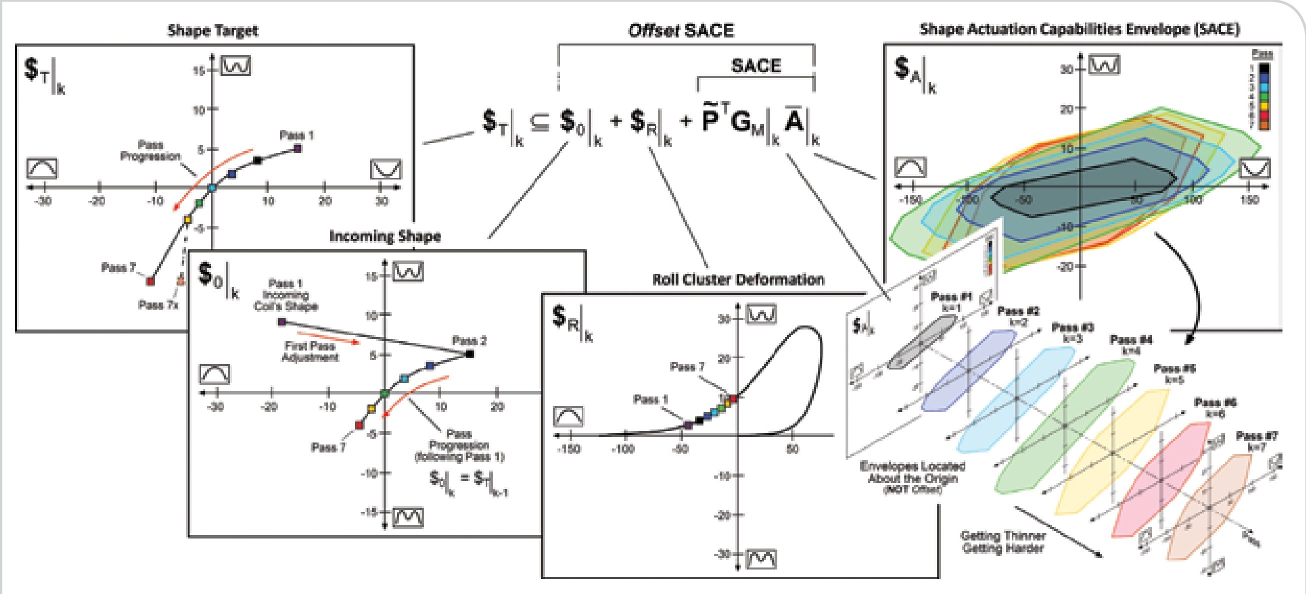
The sequential design procedure is illustrated in the block diagram of Figure 8 and described in the following:

Figure 6



The relationship between the real-world spatial waveforms, the parametric decomposition transformation and the abstracted spatial curvature representations.

Figure 7



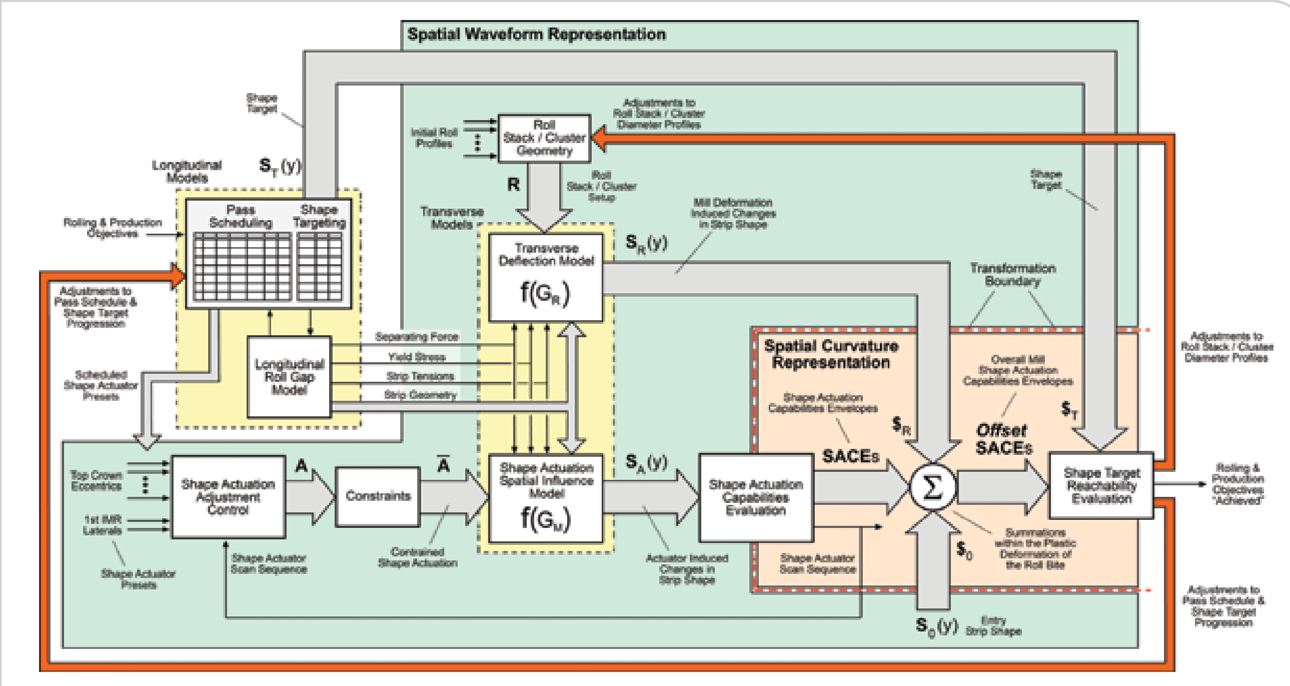
Diagrams showing the focal point of the design process and the pass-to-pass components forming the *Offset* SACE.

1. The pass schedule's reduction plan and production objectives, along with the mill and material characteristics, are applied to the longitudinal roll gap model,[4–10] which determines the parameters defining the nature of each pass' operating point.
2. The longitudinal model results are passed to the transverse models to determine the spatial waveform characteristics of the roll stack/cluster and the shape actuation for those specific operating point conditions.
   a. Using the initial roll stack/cluster setup, the transverse deflection model[19,21] predicts the mill's natural separating force loaded deflection, and its spatial waveform contribution to the rolled strip shape, $\mathbf{S}_R(y)$.
   b. Using the shape actuator settings, **A**, constraints are applied and passed to the spatial influence model,[1–3,4] which determines their spatial waveform contributions to the rolled strip shape, $\mathbf{S}_A(y)$. A scanning/survey method[1,3] is applied to determine the SACEs by adjusting the shape actuators over their entire constrained range of operation (note the feedback pathway to the shape actuation adjustment control).
3. Along with incoming strip shape, $\mathbf{S}_0(y)$, and shape target, $\mathbf{S}_T(y)$, the parametric decomposition transform is applied to these components ($\mathbf{S}_R(y)$ and $\mathbf{S}_A(y)$) to render the *Offset* SACE.[2]
4. The shape target reachability criteria[1–3] (of Figure 7) are applied to determine whether the spatial curvature representation of the shape target, $\$_T$, resides within the *Offset* SACE for that specific pass (Figure 9a).
   a. If it does, the shape target, $\mathbf{S}_T$, is "reachable"[1–3] and the objectives of that pass can be achieved.
   b. If the $\$_T$ does not reside within the *Offset* SACE, the shape target, $\mathbf{S}_T$, cannot be achieved and the shape actuation system will engage its constraints. Adjustments to the roll stack/cluster's deformation contribution, $\$_R$, must be made through the curvature influences of the pass schedule and mill setup (depicted by orange highlighted feedback pathways in Figure 8).

Directions of Adjustment and Performance Improvement — Within the abstracted curvature space, when confronted with non-reachable shape target situations, the question of what to change and by how much is immediately resolved by examining the manner in which adjustments to the roll stack/cluster deformation contribution, $\$_R$, provided by changes to the pass schedule (primarily reduction and separating force) and the mill setup (the mechanical compensation for separating force-loaded deflection), cause the *Offset* SACE to translate in the curvature space.[2]

Recalling the orange highlighted feedback pathways of Figure 8, and considering Figure 9b, a change in the pass schedule to take less reduction

Figure 8

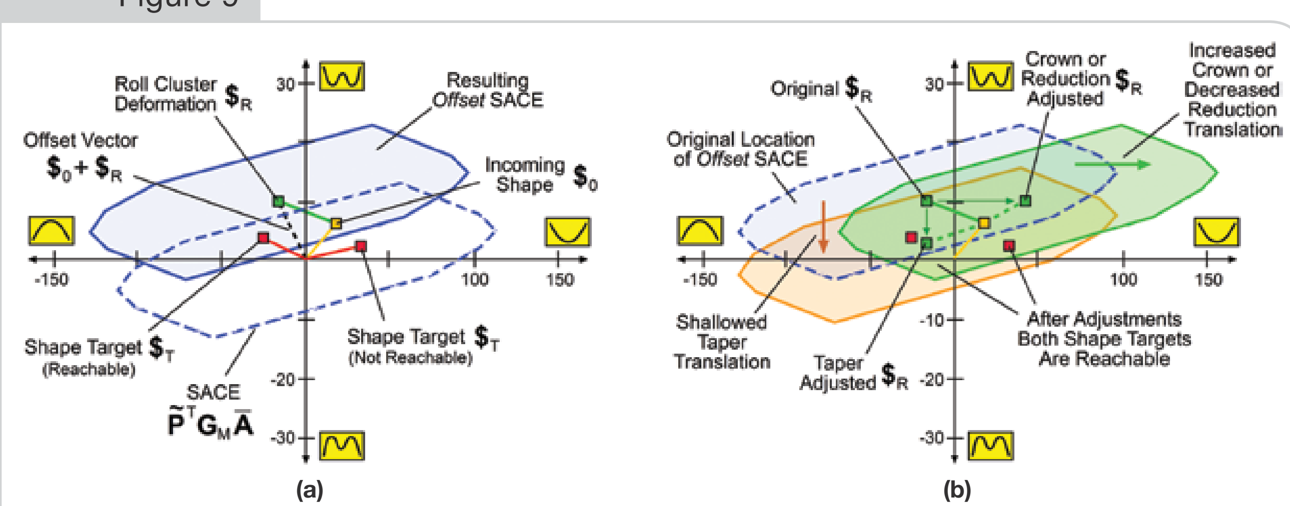


Block diagram illustration of the procedural design sequence and information flow.

(subsequently reducing the separating force and associated deflection) or an increase in the roll stack/cluster mechanical crown cause the *Offset* SACE to translate to the right. Also shown is that a change in the first IMR taper to a shallower slope causes the *Offset* SACE to translate downward.

With a knowledge of these translating directions and sensitivities, and through the adjustment/tuning/feedback pathways, the design coordination is realized, which allows the *Offset* SACE to be specifically and strategically maneuvered (via coordinated changes to the pass schedule and/or mill setup) to overcontain the shape target curvature, $\$_T$, and thereby satisfy the reachability criteria of Figure 7.

Figure 9



Diagrams showing the formation of the *Offset* SACE (a), and how changes to the pass scheduled reductions or mill setup induce a shift in the *Offset* SACE (b).

Conclusion

This article presented a systematic, procedural method for coordinating the pass schedule, shape target progression and mill setup designs by performing the work in an abstracted framework employing spatial curvature representations. These curvature space representations (parametric decompositions of the induced, real-world spatial stress waveforms) are abstracted from the mill arrangement, thereby removing the consequences of the mill's physical configuration and operation. The design framework focuses only on the fundamental roll bite behavior, mechanical deformation, material reaction and shape actuation characteristics. The combined/coordinated mill setup, pass scheduling and shape targeting design is carried out in this abstracted curvature space, then transformed back to reality for direct implementation. The family of solutions (in this abstracted framework) provide well-defined guidance and directions of performance improvement with suggested adjustment amplitudes.

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